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Sleep Apnea Surgery: 23 Years of Collaboration Between Drs. Christian Guilleminault and Kasey Li

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John Libbey Eurotext

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John Libbey Eurotext

Publisher
John Libbey Eurotext
30 rue Berthollet
94110 Arcueil, France
Tél. : 01 46 73 06 60
contact@jle.com
www.jle.com

President and CEO
Gilles Cahn

Editorial Secretary
Dominique Vatan (07 63 58 96 40)
dominique.vatan@jle.com

Marketing
Arnaud Cobo (07 63 59 03 35)
arnaud.cobo@jle.com

Partnerships and advertising
Account Manager
Noëlle Croisat (07 63 59 03 68)
noelle.croisat@jle.com
Advertising Manager
David Laifer (07 63 59 03 94)
david.laifer@jle.com

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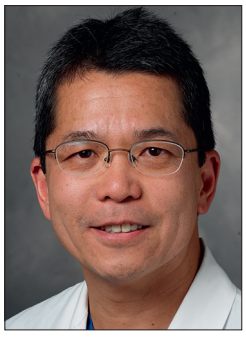

I met Dr. Christian Guilleminault in 1997 when I was starting my career as a young surgeon.

Over the years, our relationship evolved from a mentorship to a partnership and, ultimately, a friendship.

Few people are aware of how tirelessly he worked and the sacrifices he had made to advance Sleep Medicine to what it is today.

An example of his dedication was made clear on a flight home after giving a lecture in China. It was in the middle of the night and the entire plane was dark, quiet and passengers were sleeping. I woke up and headed to the back of the plane to use the washroom. I noticed a lone seat with its overhead light turned on. As I got closer, I saw Christian hovering over a thick stack of manuscripts. Unfortunately, and fortunately for me, he looked up and excitedly asked me to review one of the manuscripts and give him feedback before we landed. Needless to say, I was up for the duration of the flight. You just can't say no to Christian.

The life of a trailblazer is a lonely one. Christian was openly mocked because mere mortals could not understand or accept his pioneering work, and his description of the upper airway resistance syndrome (UARS) was the most controversial. Despite this, Christian never veered off his course, and although it took years, it is safe to say that respiratory effort related arousal (RERA) and UARS are well-recognized entities in sleep. Christian wasn't always right, but he was rarely wrong.

Dr. Christian Guilleminault had a huge impact in my professional life. There is no doubt that his friendship and mentorship made a positive difference in my career. It is a great honor to be invited and to contribute to the Orthodontie Française.

The following papers represent what I have learned, observed and developed in the past 25 years. I hope they will be beneficial to the readers.

Kasey Li

* Correspondance : drli@sleepapneasurgery.com

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Obstructive sleep-disordered breathing and orthodontics. An interview with Christian Guilleminault, Michèle Hervy-Auboiron, Yu-Shu Huang and Kasey Li*

Christian GUILLEMINAULT[1], Michèle HERVY-AUBOIRON[2**], Yu-Shu HUANG[3], Kasey LI[4], Philippe AMAT[5]

[1] University, Faculty of Stanford, 401 Quarry Rd, Palo Alto, CA 94304, USA
[2] 75 rue Jean-Jaurès, 93130 Noisy-le-Sec, France
[3] Department of Pediatric Psychiatry and Sleep Center, Chang Gung Memorial Hospital, No. 5, Fusing St, Kwei-Shan Township, Taoyuan Country, 333, Taiwan
[4] 1900 University Ave #105, East Palo Alto, CA 94303, USA
[5] 19 place des Comtes du Maine, 72000 Le Mans, France

** Translated by Philippe Amat. Original article published in French in l'Orthodontie Française (Orthod Fr 2019;90:215-245). With the agreement of the journal and the publisher.*

N.D.R. The implementation of this interview was mourned by the departure of Christian Guilleminault, during the correction phase of the print orders.

Prof. Christian Guilleminault is the author or co-author of 13 books and has published over 826 articles in peer-reviewed journals. He has lectured in most countries and has received 37 awards and honours for his contributions to neurology, sleep disorders and sleep medicine in the US and from international organisations.

In 1963, Christian Guilleminault passed the competitive examination to become an intern at the Hôpitaux de Paris. He began his first research projects at the Foch Hospital and the Orsay Faculty of Sciences. After passing his thesis in 1968, as a young Doctor of Medicine, he began his work on sleep pathologies. He trained in neurology mainly at the Salpêtrière Hospital in Paris and, after completing his studies in neurology, he became a Doctor of Medicine.

He trained in psychiatry in Geneva and Paris. He obtained a diploma of advanced study from the Faculty of Sciences of the University of Paris (histology and histochemistry) and was certified in neurology and psychiatry in 1970. He was appointed Senior Scientist at the National Institute of Health and Medical Research (INSERM) in Paris in 1977.

He obtained the Habilitation to direct research (HDR) from the Faculty of Medicine of the University of Montpellier in 1998, and a PhD in Biology/Neurosciences from the University of Grenoble in 1999.

He was appointed Associate Professor of Psychiatry and Behavioural Sciences at Stanford University in 1980, and then Full Professor of Neurology in Psychiatry, Department of Psychiatry and Behavioural Sciences and (Courtesy) Neurology, Stanford University School of Medicine in 1985. Visiting Professor at the University of Marburg (Germany) and recipient of a Humbolt Fellowship in 1987-1988, he was also Professor without tenure at the Montpellier Medical School in 1994-1996.

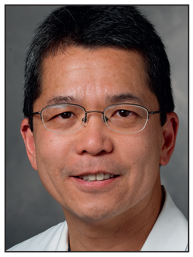
Currently, he is a Professor in the Department of Psychiatry and Behavioral Sciences and, by courtesy, in the Department of Neurology at Stanford University School of Medicine and a Full Professor in the Division of Sleep Medicine at Stanford University. He is a member of the American Electroencephalographic Society and the American Academy of Sleep Medicine (AASM).

** Correspondance : michelehervy@mac.com

Dr. Michèle Hervy-Auboiron is a doctor of dentistry and a qualified specialist in orthodontics. She holds a Certificate of Special Clinical Studies in Orthodontics, a University Diploma in Occlusodontology, a University Diploma in Maxillofacial and Oral Expertise and an Inter-University Diploma "Sleep and pathologies". She regularly collaborates and publishes[30,77,119] with Christian Guilleminault.

Prof. Yu-Shu Huang graduated from Chang Gung University in Taiwan. She trained in psychiatry and pediatrics at Chang Gung Memorial Hospital. She also trained in sleep medicine at the Stanford Sleep Center in 2003, under the supervision of Professor Christian Guilleminault. She then completed her PhD at the Faculty of Medicine of the University of Lisbon. Her clinical and research interests are in pediatric psychiatry and sleep medicine. She has published more than 100 articles in peer-reviewed journals, including paediatric hypersomnia, narcolepsy, obstructive sleep apnea in paediatrics and attention deficit disorder with or without hyperactivity (ADHD). She is a professor in the department of child and adolescent psychiatry.

She is currently Director of the Department of Child and Adolescent Psychiatry at Chang Gung Memorial Hospital in Taipei, Taiwan. She is currently also the Director of the Department of Child and Adolescent Psychiatry at Chang Gung Memorial Hospital.



Dr. Kasey Li has a long academic and professional career. Specialising in the treatment of obstructive sleep apnoea, Dr. Li is the only surgeon in the world to be certified by three American Boards: the American Boards of Otolaryngology, Oral and Maxillofacial Surgery, and Facial Plastic and Reconstructive Surgery. Based on his unique background and experience, he has developed and refined many surgical techniques for sleep apnea. Dr. Li is the surgical consultant for many sleep disorder treatment centres, including the Stanford Sleep Disorders Clinic's multidisciplinary sleep treatment team. He has published more than 100 scientific articles and book chapters on sleep apnea surgery and maxillofacial surgery. By invitation, Dr. Li has lectured extensively in the United States and abroad as an internationally recognized expert in sleep apnea surgery.

Philippe Amat: *The relationship between sleep medicine and orthodontics is a subject of constant interest for our disciplines, as shown by the programmes of their respective congresses and the many publications devoted to them over the last thirty years. We would like this interview to provide our readers with a summary of some of the key elements of this relationship and to shed light on the many facets of your important contributions to the creation and development of "sleep medicine" as a new field of medicine throughout the world.*

Christian Guilleminault, Michèle Hervy-Auboiron, Yu-Shu Huang, Kasey Li: We are pleased to answer the questions in this interview in order to provide the readers of the Orthodontie Française with a summary of the various medical dimensions of sleep disorders and the contribution of orthodontics to their treatment. We also welcome this initiative by the Orthodontie Française to bring together in a special issue, almost a monograph, most of the current data on the interrelationship between obstructive sleep disorders and orthodontics.

1. Your academic background

Philippe Amat: *Professor Guilleminault, in December 2013 you gave an interview[74] to the Sud-Ouest newspaper in which you spoke of the scepticism that greeted your first research in France. You declared: "Nobody believed in it. In France, I was an idiot. Considered naive. My career, when I was a young and curious neurologist, was blocked". Is this the reason why you decided to accept the position of assistant professor in the Department of Psychiatry and Behavioural Sciences at Stanford, which William Charles Dement offered you in 1971, in Bruges, during an international congress on sleep?*

Christian Guilleminault: Certainly, it was an opportunity for me to progress in my research. In Paris, my boss allowed me to continue my research, but without giving me the time or the budget. I was forced to carry out nightly examinations of patients, electrocardiograms, electroencephalograms, breathing, muscles and movements at my own expense. My management had told me that "sleep is for dreamers". So I worked day and night and paid for the electrodes needed for the recordings. This allowed me to consider a thesis. I observed respiratory disorders in ordinary people, non-obese children. I observed periodic breathing but nobody believed it.

PA: *You said[74] "I came to California with my 450 recordings and my files". What resources did you have at Stanford?*

CG: A few months after the Bruges International Congress, I moved to California and took up a position as assistant professor in the Department of Psychiatry and Behavioural Sciences at Stanford. My research was able to develop more easily thanks to the means at my disposal. In addition to an office, a laboratory and funding, I was able to gather a team of researchers at my side.

PA: *Before you went to Stanford, you had opened the first sleep laboratory in Paris in 1970. Why did you become interested in what was to become sleep medicine?*

CG: At the time, snoring and night-time breathing problems were attributed to the very obese who suffered from hypersomnia: the Pickwick syndrome, named after the character in a novel by Charles Dickens, described in 1956.

I was convinced that apnoea syndrome can affect anyone, causing various disorders: hypertension, cardiac arrhythmias, exhaustion. In non-obese children, brought to consultation for attention or memory problems, hyperactivity, enuresis or sleepwalking, I had diagnosed sleep apnoea.

PA: *Our daily clinical practice has convinced us that, while the evidence-based approach[3] is a good guide, it can also become a bad teacher. In an interview[136], Prof. J.-D. Orthlieb had stigmatised the utopian aspect of evidence-based medicine and pointed out the risk that it would promote "a new form of scholastic ostracism". He said: "By its clarity and rigour, deductive reasoning appears at first sight as the essential instrument of scientific progress. But, in an incomplete science that is being created and that is progressing, L. de Broglie asserts that inductive reasoning is the true source of great scientific progress. It is necessary to leave room for both the necessary reason and the indispensable freedom of the imagination. Thus observation, the luminous idea, obvious in itself, will enlighten. Then, rigorous experiment will instruct and validate".*

Since 1972 and your first publications on sleep apnoea[42,43,67], your career as a clinician, researcher and teacher seems to show that you have not taken account of fixed opinions, academic and administrative blockages. What is your approach to scientific research?

CG: Research is indeed dual, inductive and deductive. I would like to stress that a methodologically rigorous demonstration through randomised double-blind clinical trials over a sufficiently long period of time is always necessary before we can say that a therapy is effective and what the possible complications are, and this is too often not done. The constant aim of medical research is to help improve the health of patients and requires great determination on the part of the researcher, as you have mentioned. It also requires curiosity, open-mindedness, scientific rigour and the ability to bring together and share knowledge.

PA: *Michèle, we met at the University Diploma of Occlusodontology of Paris V directed by Claude Michel Valentin. Can you describe the rest of your univer-*

sity career and the motivations behind your choice of post-graduate training?

Michèle Hervy-Auboiron: It was precisely during this DU that I became interested in sleep apnea-hypopnea syndrome (SAHOS). At the time, the mandibular advancement orthoses were beginning to become a therapeutic alternative of choice and Bernard Fleiter had suggested that I focus my dissertation on their potential side effects, and even on proposals to reduce them. On the judicious advice of Alain Lautrou, I worked on a more functional project. Subsequently, CG recommended that I take the DIU Sleep and Pathology, in order to deepen my general knowledge of the subject

PA: *When we met, I often witnessed the constant and friendly complicity between you and Christian Guilleminault. Under what circumstances did you meet and how did you come to work together?*

MH-A: I had developed a medical device for functional rehabilitation: the SomNyx®, which was the winner of the OSEO Emergence competition in April 2012. Friends of mine who are ENT specialists, including Frederic Chalumeau, asked me to accompany them to San Francisco for the American Thoracic Society conference and they asked CG to meet them at Stanford. CG was totally on board with the treatment plan. He immediately considered two studies, one in children in Taiwan and one in adults in France and Canada. We couldn't have asked for better support. The complicity you mention reflects both a sincere friendship and a deep respect.

PA: *Professor Yu-Shu Huang, you have completed your academic training in three continents, at Chang Gung University in Taiwan, the Stanford Sleep Center and the University of Lisbon Medical School. Can you share with our readers the key elements of your educational choices and your current clinical and research interests?*

Yu-Shu Huang: I completed my training in psychiatry and pediatrics at Chang Gung Memorial Hospital. In 2000, Chang Gung Memorial Hospital opened the largest sleep centre in Asia and I was asked to go to Stanford University to learn sleep medicine from Professor Guilleminault. Back in Taiwan, I continued to work with Professor Christian Guilleminault on sleep medicine studies. In particular, I undertook research on paediatric attention deficit hyperactivity disorder (ADHD) and obstructive sleep apnea (OSA).

In addition, together with Professor Guilleminault, I have published numerous studies on paediatric hypersomnia (Kleine-Levin syndrome) and narcolepsy. In 2012, Professor Guilleminault thought that there were important correlations between premature babies and sleep apnoea. So he suggested I go to the University of Lisbon to specialise in sleep medicine. Professor Teresa Paiva had agreed to direct my PhD thesis and she proposed the topic "Premature babies and sleep-disordered breathing in children". Therefore, my main interest today is in paediatric sleep medicine, with a focus on paediatric sleep apnoea and paediatric hypersomnia.

PA: *You are currently Professor in the Department of Child and Adolescent Psychiatry at Chang Gung Memorial Hospital in Taipei, Taiwan. What differences have you observed as a teacher, and previously as a student, between Taiwan, the US and Europe?*

Y-SH: You are right to mention these differences. Yes, in Taiwan, the US and Europe, the situation is different, not only for the teachers but also for the students. In Taiwan, the students, especially the medical students, who are usually very good students who have made it to medical school, are more passive during their studies. During lectures they are always quiet and are rarely asked to speak. Very few students will proactively ask questions, as they see their teacher as the authority. Taiwanese students usually lack self-confidence and a global outlook. The teachings of Taiwanese teachers are also traditional and rely on the use of textbooks. There is also less opportunity for teachers and students to interact after class.

In the United States, it is open education. The distance between teachers and students is smaller. Students are strongly encouraged to ask many questions in class. The relationship between teachers and students is sometimes like a camaraderie. I was not used to it at the beginning.

In many European countries, I have felt the strength of tradition and the influence of a rich

historical past. The relationship between students and teachers is halfway between those I experienced in Taiwan and the United States. The students' learning attitude is active and polite towards the teachers. But students and teachers respect each other. The pervasiveness and weight of historical culture is probably the most important difference between Europe and the US.

PA: *Kasey, you are the only surgeon in the world certified by the American Boards of Otolaryngology, Oral and Maxillofacial Surgery, and Facial Plastic and Reconstructive Surgery. Can you tell our readers about the key stages of your academic career?*

Kasey Li: My father was an ear, nose and throat specialist, but I decided to study dental surgery. I first graduated from UCLA dental school and then spent a year doing research. I then enrolled in the Oral and Maxillofacial Surgery Residency Program at Harvard, where I also earned a medical degree. Immediately after completing my oral surgery training, I entered the otolaryngology/head and neck surgery program at Harvard. After spending a decade in Boston, I returned to California and did a fellowship in facial plastic surgery before coming to Palo Alto where I met the hard-headed Frenchman.

PA: *When did you first meet Christian Guilleminault? What projects did you carry out together and to which you dedicated publications?*

KL: I first met Christian in 1997 when I started practicing at Stanford. Because of my training, it was natural to start working closely with him. We started the multidisciplinary treatment clinic in 1998 at the Stanford Sleep Clinic, which was called the Friday Clinic. It was every Friday afternoon between 1 pm and 4:30 pm and we had wine and cheese with the colleagues afterwards. Of course Christian drank all the wine because I didn't! It was a good time and I have fond memories of it. We discussed a lot of treatment options and presented alternatives to CPAP. We received many families with parents and their children at the same time. All my sleep publications were with Christian and they covered 90% of my academic work.

2. From obstructive sleep apnea syndrome to upper airway resistance syndrome

PA: *Christian Guilleminault, the readers of French Orthodontics know you through your conferences, publications and books. You are one of the founding fathers of sleep medicine, you created the first sleep laboratory in Paris in 1970 and after defining the obstructive sleep apnea syndrome[42,43,67], you have and continue to publish an amazing volume of research. Since the description of "Pickwick's syndrome"[10], what have been the key milestones in the recognition of obstructive sleep apnoea syndrome (OSA) in non-obese adults and in children?*

CG: The subject is vast. Decades of research and questioning have led to the recognition of obstructive sleep apnea syndrome in adults and children. After Bickelmann, *et al.*[10] proposed the name "Pickwick syndrome", the German school was the first to register these obese subjects

The results of this study were used to identify "Pickwickian" sleep patterns and to show the presence of "obstructive apneas" during sleep.

In 1962, Werner Gerardy, *et al.*[38] found "repeated obstructive apnoea" on polygraphic recordings of two obese patients and a return to normal breathing with significant snoring associated with tachycardia. Kuhn[90] (Kuhlo after his name change) continued this early work and ensured the international dissemination of their results. The therapeutic success of tracheotomy[97], which he was the first to perform in a Pickwickian, demonstrated that sleepiness was related to sleep fragmentation caused by apnoea.

Other researchers, such as Gastaut and Lugaresi[129], have complemented the work of the German school by studying the cardiovascular events occurring during sleep apnea in obese Pickwickians.

Organised in 1972 in Italy by Lugaresi and Sadoul, the "Hypersomnia and Periodic Breathing" symposium was the first international meeting where sleep apnoea was the focus of debate. William C. Dement from Stanford University was invited and had little knowledge of the topic and asked me to represent him. I presented the evidence that sleep

apnoea was not exclusive to obese Pickwickians but could be seen in normal weight patients[42].

The term "obstructive hypopnea" originated from the observation by Londsdorfer, Kurtz[98] and Krieger[96] that upper airway obstruction could be incomplete and still induce arousal responses on the electroencephalogram.

The polygraphic recordings of B. Duron[35] allowed him to dissociate obstructive, mixed and central apnoeas.

Finally, in order to assert the existence of a syndrome independently of an association with obesity, with WC. Dement, we proposed[67] the entities "sleep-apnea-syndrome", and "obstructive sleep-apnea-syndrome (OSAS)".

PA: *How did polysomnographic studies and the use of an oesophageal pressure probe then lead you to the description of abnormal upper airway resistance in the child[52,61,64,68]?*

CG, MH-A, Y-SH, KL: We had accumulated paediatric case reports and demonstrated that OSAS can cause multiple complications[53]. We described children with clinical signs and symptoms similar to those seen in sleep apnoea without any apnoea or hypopnoea on the nocturnal polygraph recording. In the 1982[68] publication you quoted, it was indeed by measuring respiratory effort with an oesophageal pressure probe that, in these children, we identified increased respiratory effort as the only abnormal element in the recording. We described the multiple symptoms of this abnormal resistance of the upper airways, without any real impact on oxygen saturation, but associated with repeated disturbances of the electroencephalogram (EEG) during sleep.

Y-SH: Polysomnography (PSG) is used to monitor abnormal upper airway resistance, including nasal cannula pressure transducer, oral thermistor, chest and abdominal bands (RIP belts), pulse oximetry, neck microphone and Intercostal EMG (ICR). Esophageal pressure (EP) is not routinely monitored, but will be useful in doubtful cases.

Historically, "hypopnea" was defined at a time when breathing at the nose and mouth was monitored by thermistors that measured temperature changes and with an oximeter of limited accuracy. The definition of hypopnoea (hypopnoea can be assessed with a 3% drop in SaO2 or a micro-awakening of 3 seconds or more on the electroencephalogram (EEG)), which is still sometimes used, is related to these recording difficulties. But now we have the "nasal cannula pressure sensor", we have a better oximeter, and we know that cortical disorders related to abnormal breathing are important consequences of the problem.

PA: *What clinical consequences of this abnormal upper airway resistance have you identified on children's attention, memory, academic performance and daytime hyperactivity?*

CG, MH-A, Y-SH, KL: We had described the multiple symptoms[68], in particular inattention, daytime hyperactivity, impact on memory, school results, clinical consequences of this abnormal upper airway resistance. Since this 1982 publication, other research work has been carried out. They show that sleep-disordered breathing can affect the physical and mental health of children, with growth disturbances, cardiac and metabolic problems.

Studies of children with OSA and attention deficit hyperactivity disorder (ADHD), published in 2004[76] (Journal of Sleep Research) and 2007[81] (Sleep Medicine Journal), also showed that in children with OSA treated with adenotonsillectomy, ADHD symptoms improved significantly.

KL: Christian had great clinical acumen and had built up so much experience that he could see things and understand things that others could not. I would only report that in the early days of High Resistance Upper Airway Syndrome, colleagues would come on stage and openly mock Christian with a fake French accent! Of course not, this didn't bother Christian. He continued his research, describing multiple hitherto unknown paediatric symptoms, helping so many children that others had simply dismissed!

PA: *Your investigations in adolescents and adults have led to the description of Upper Airway Resistance Syndrome (UARS)[63,65,165,166]. What is the clinical picture, what are the main consequences, including cardiac and*

cognitive consequences, and why are patients with HVAS still sometimes undiagnosed and untreated[138]?

CG, MH-A, Y-SH, KL: Initial ignorance of the possibility of abnormal upper airway resistance in children may have been due to the lack of use of an oesophageal probe in polysomnographic studies in most laboratories. We continued our studies and extended their initial scope from children to adolescents and adults. The accumulation of our observations led us to the description of a clinical picture in adults, which we published under the name of "high resistance syndrome of the upper airways"[62]. We showed that this HVAS was associated with snoring and had numerous consequences, notably cardiac and cognitive. Since then, the introduction of nasal cannulae with pressure recording has meant that we are no longer routinely required to use esophageal pressure recording to study airflow limitations.

There is no gender predominance in SHRVAS. Subjects are generally non-obese, with a body mass index (BMI) ≤ 25kg m^2, and often younger than OSA patients.

Patients with ARVHS experience daytime sleepiness or fatigue, and have impaired cognitive function and even heart rate instability. We have shown that their symptoms overlap with those of OSA patients, with their own characteristics[41]. In them, chronic insomnia tends to be more frequent, sometimes with night-time awakenings and difficulty in returning to sleep. They often complain of sleep insomnia and maintenance insomnia, thought to be due to "conditioning", because of frequent sleep disturbances[57]. Parasomnias such as somnambulism and sleep terrors, myalgia, depression and anxiety have also been reported.

Despite the difference in clinical features, it is sometimes difficult to distinguish patients with ARVAS from those with mild OSAS, based on symptoms and clinical signs alone. The diagnosis can only be confirmed by polysomnography. Nocturnal PSG shows no apnoeas or hypopnoeas and respiratory abnormalities consist of periods of increased respiratory effort, fragmentation of sleep, presence of micro-arousals associated with a high resistance event and flattening of the respiratory curve, indicating airflow limitation.

It should be noted that ARVHS can frequently be misinterpreted as chronic fatigue syndrome, fibromyalgia, or psychiatric disorders such as attention deficit disorder with or without hyperactivity (ADD/ADHD)[107].

PA: *In 2018, you wrote that the terms Upper Airway Resistance Syndrome, Obstructive Sleep Apnoea Syndrome and Hypopnoea Apnoea Index are only historical[7]. You recalled that we now have a better understanding of the development of sleep-disordered breathing and its evolution with age, leading to comorbidities. You pointed out that our current knowledge is now sufficient to go beyond these definitions, to recognise the problems differently, much earlier, and to prevent the factors leading to sleep-disordered breathing. Can you explain how the recognition of non-hypoxic sleep-disordered breathing[45] is a step in this direction?*

CG, MH-A, Y-SH, KL: Indeed, upper airway resistance syndrome (UARS), known as obstructive sleep apnoea syndrome (OSA), was described as abnormal breathing during sleep, based on recording technology and knowledge at the time. Although the definition of these terms has advanced sleep medicine, they are less useful today. Historically, the definition of SHRVAS was intended to recognise those conditions not covered by "OSA" and to encourage specialists to recognize conditions earlier and to prompt research into the developmental characteristics of sleep-disordered breathing (SDB). The technology used to monitor SDB has changed over time, resulting in different, but not necessarily better, recognition of SDB.

Sometimes, patients are not diagnosed with sleep-disordered breathing or obstructive sleep apnoea until they are 40 years old. This is unfortunate, as SDB at this age is accompanied by various comorbidities, including excessive daytime sleepiness, increased risk of traffic accidents and cardiovascular complications. The real issue is therefore to recognise the problems much earlier and to understand what can be done to prevent their development.

By analysing different patterns of abnormal breathing (Fig. 1) such as flow limitations, mouth breathing, changes in inspiration and expiration times, chest and expiratory muscle activity, snoring sounds, etc., it is possible to recognise cases of

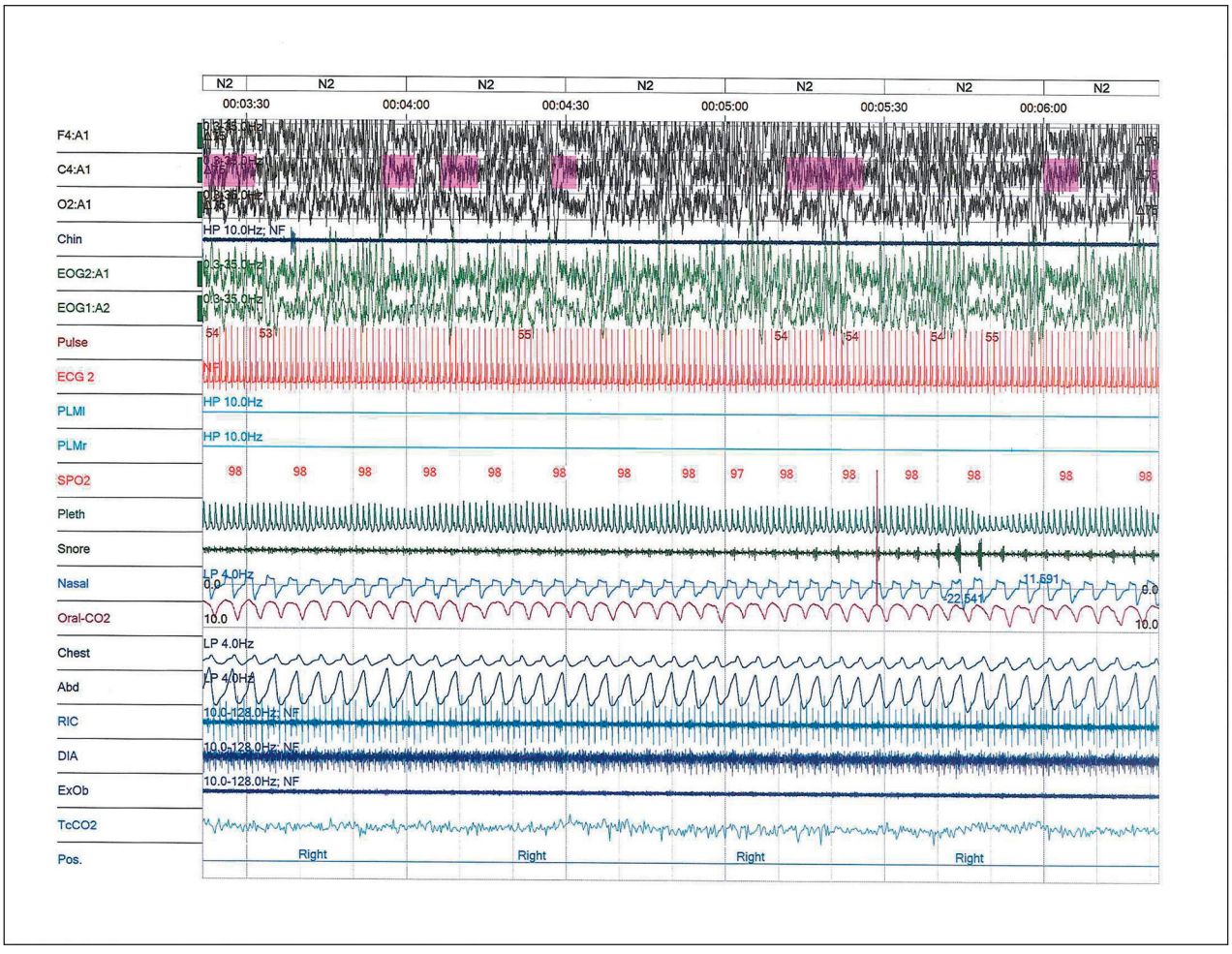


Figure 1

Monitoring of oral respiration. The Oral-CO2 channel (15th from the top) indicates continuous mouth breathing. Here it is associated with flow limitation and snoring develops after mouth breathing. According to Christian Guilleminault, some EEG indicators (including the CAP –cycling alternating pattern– which is an EEG marker of sleep instability) present in patients with SHRVAS (pink fluorescent areas on the C4:A1 EEG channel) are too often ignored, although they testify to the impact of any flow limitation on sleep quality and its consequences on cognitive performance.

"non-hypoxic" sleep disorder. By going beyond the traditional notions of apnoea-hypopnoea and hypoxic sleep disordered breathing, which are still favoured by clinical practice guidelines, we can avoid delaying the treatment of these children and prevent the progression of their SDB.

PA: *Obstructive sleep-disordered breathing (OSDB) is associated with increased respiratory effort, of which oesophageal pressure is the gold standard, but it is generally poorly tolerated because of its invasiveness. You have shown[70] that a machine learning computer technique can be used as a tool to quantify respiratory effort from routinely collected non-invasive polysomnography measurements without the need for oesophageal pressure. What are the future prospects for this technique and for OSDB diagnosis more generally?*

CG, MH-A, Y-SH, KL: Yes, we can now use Artificial Intelligence (AI) as the self-learning computer program ("machine learning", "deep learning"). Computers are given the ability to "learn" from data, i.e. to improve their performance in solving tasks without being explicitly programmed for each one. The use of AI can help us with some difficult interpretations of PSG, such as quantifying respiratory effort, or to build some predictive models.

PA: Numerous sleep analysis applications for smartphones provide data on sleep patterns, but none of them have been successfully validated by polysomnography to date[127,135]. Applications to assist in self-care sleep management have also been developed but their reliability has not been addressed due to a lack of validation studies[28].

Can we expect an increase in the sensitivity and specificity of these applications compared to polysomnography, which would profoundly change the management patterns of SDB?

CG, MH-A, Y-SH, KL: There are currently many sleep application programs, most of which are primarily developed using heart rate, pulse and respiration. But "breathing" is a complex function involving different anatomical regions such as the nose, mouth, chest, abdomen and brain. Breathing is controlled by different parts of the brain, including the brainstem and cortical regions. The relationship between "breathing, heart and brain" is therefore particularly complex and dynamic. This is the limitation of the applications currently available for download. If these programs could increase the signal or information from the brain, their reliability should increase.

3. OSDB for children, adolescents and adults

PA: *Dr. Olivier Revol, child psychiatrist and head of the Neuropsychiatry Department at the Pierre-Wertheimer Neurological Hospital in Lyon, told us in an interview[4] that "I preferred child psychiatry to adult psychiatry, where the possibilities of improving old pathologies are very limited. Early detection allows for early intervention, with appropriate care and often quite mild. The treatment is quickly effective and changes the future of the young patient completely. Not intervening often means allowing a sympatology to set in, the long-term consequences of which can be extreme, if not serious, at least complicated for the child".*

Is it a similar aspiration that drives you to devote so much energy and time to the care of the child's OSDB?

CG, MH-A, Y-SH, KL: We share Olivier Revol's view, which applies perfectly to the field of sleep. If there is no intervention on the factors that have an adverse impact on orofacial growth early in life with regular monitoring, obstructive sleep apnea (OSA) will occur and worsen with age. We would particularly like to draw your readers' attention to this important point.

We have shown that subtle abnormalities in oropharyngeal growth in infants and young children can contribute significantly to sleep disordered breathing and OSA later in life.

If left untreated, OSA affects children's quality of life, neurocognitive and academic performance, growth, behaviour, cardiovascular, carbohydrate and lipid systems.

Neurocognitive morbidity, which is reflected in hyperactivity, irritability, or even attention deficit disorder with or without hyperactivity (ADHD).

Agitation, lack of concentration or memory are often at the forefront and can be responsible for difficulties or delay in school. Indeed, repeated episodes of apnoea or hypopnoea are responsible for awakenings and micro-awakenings, leading to fragmentation and poor quality of sleep. Thus, it is important to look for OSA in any child with ADHD.

An improvement in neurocognitive disorders is observed after treatment of OSA in the vast majority of cases.

Cardiovascular morbidity, although less severe than in adults, is present with repeated episodes of airway obstruction which are associated with sympathetic hyperactivation with increased heart rate and blood pressure.

3.1. OSA and craniofacial growth

PA: *Harvold's work[71,178] has shown that dysfunctional nasal ventilation induces postural adjustments of the orofacial musculature and abnormalities in hard and soft tissue development. You have described how the interaction between abnormal stimulation of bone growth and the absence of nasal breathing, which is associated with secondary amplification of oral breathing, are responsible for abnormal development of the orofacial bony structures that support the upper airways, thereby increasing the risk of upper airway collapse during sleep[93,103].*

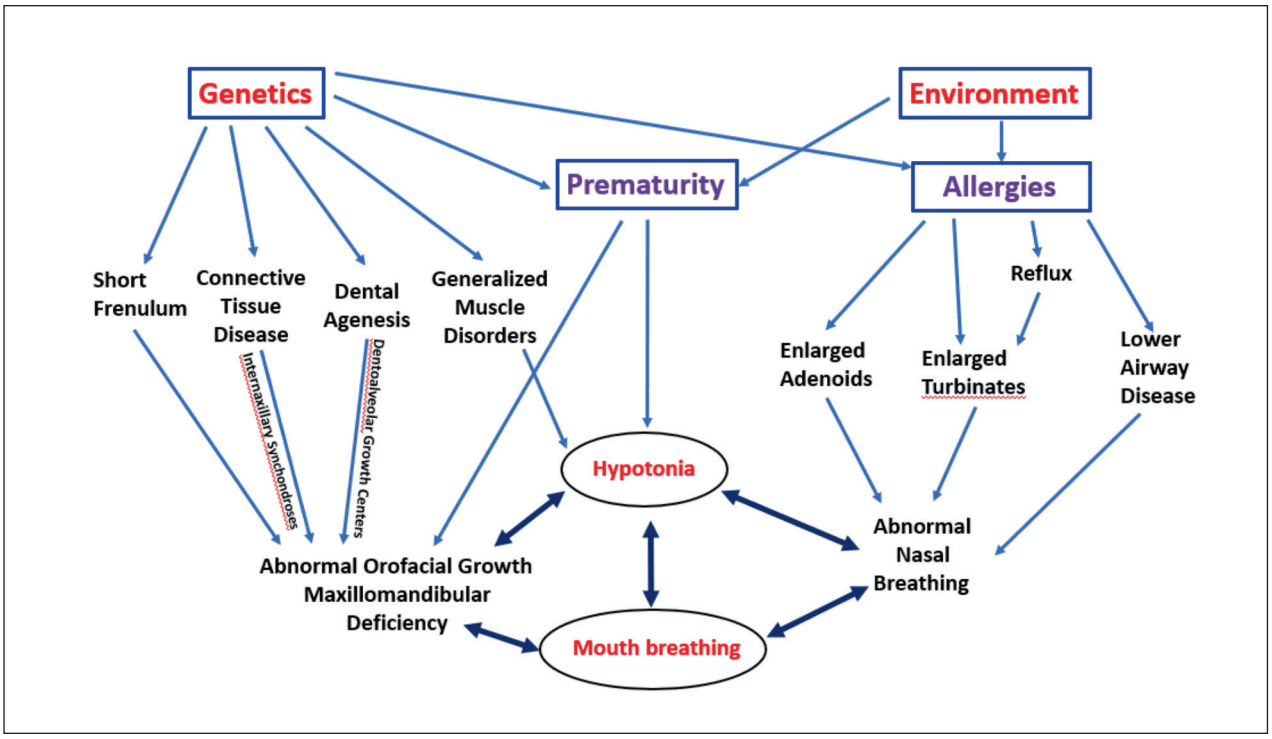


Figure 2
Abnormal development of the upper airways.

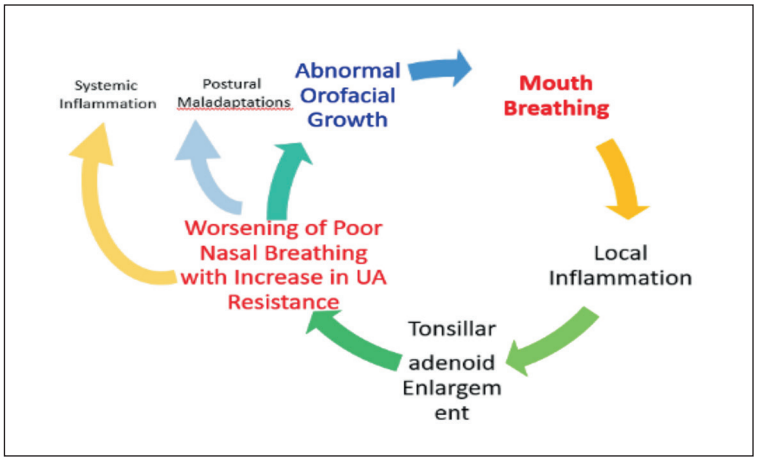


Figure 3
The vicious circle of SDB.

Before we discuss them in more detail in the following questions, can you remind us of the factors[39,40,44,48,51,78,84] that have a deleterious impact on the normal growth of the orofacial structures, and that contribute to the development of OSA in children and adults?

CG, MH-A, Y-SH, KL: Missing teeth, orofacial hypotonia, short lingual frenulum, are important factors as well as preterm birth. Our recent studies following a cohort of preterm Taiwanese children were published in BMC Pediatrics in 2014[84] and Sleep Medicine in 2019[82]. Sleep problems, neuro-developmental disorders and sleep-disordered breathing are more common in preterm infants than in term infants. We found that a very high percentage (80.6%) of preterm infants have an

AHI > 1/hour and 62.3% of preterm infants have a narrowing of the hard palate. These observations led us to propose a new concept, published in Sleep Medicine Reviews in 2018[44]: "From oral orofacial dysfunction to dysmorphism and the development of pediatric OSA". We have shown (Fig. 2) that after birth there is a continuous interaction between orofacial function and the growth of orofacial anatomical features. The dysfunctions identified to date as having a deleterious impact on orofacial development lead to sleep-disordered breathing through these disturbances in craniofacial growth.

Atypical craniofacial features, by increasing the risk of airway collapse, and oral breathing or poor nasal breathing disturbed by increased upper airway resistance, alter orofacial development.

Thus, a vicious circle is established with a continuous interaction between the factors leading to oral breathing and the oral breathing itself, which influences these factors (Fig. 3).

Therefore, the identification of risk factors, which ultimately lead to obstructive sleep apnoea, is essential. It can allow early recognition of these factors and the development of treatments to eliminate them early or at least reduce their impact, before they become more prevalent with age.

3.2. Ankyloglossia

PA: *The annual number of articles on ankylosing spondylitis has increased considerably in recent years[11]. Present in 4% to 11% of newborns, this anatomical and functional alteration of the lingual frenulum has deleterious effects on growth and craniofacial development[146,163] and may lead to breastfeeding difficulties[140] and maternal nipple pain[137]. You have shown that untreated ankyloglossia at birth is associated with OSAS in later life, and you advise that screening for the syndrome should be carried out when this anatomical abnormality is identified[51,85,184]. Can you enlighten our readers on this subject?*

CG, MH-A, Y-SH, KL: In one of our studies[184] we showed that restricted lingual mobility was associated with maxillary arch narrowing and soft palate lengthening. Our results suggest that variations in tongue mobility may affect maxillofacial development. A short, unoperated lingual frenulum at birth is associated with OSA in later life, and routine screening for the syndrome should indeed be performed when this anatomical abnormality is recognised[85].

Screening and correction of lingual frenulum shortness should be carried out early, if possible at birth, to optimize orofacial growth. Myofunctional therapy, combined with nasal breathing rehabilitation, is also necessary to restore normal sleep breathing in many children.

MH-A: A distinction must be made between the length of a frenulum and the type of anchorage of its insertions. A long lingual frenulum may nevertheless hinder lingual mobility due to its insertion levels and a short lingual frenulum hinders the proper functioning of the tongue by reducing its mobility.

As a reminder, Dahan[32] explained that the type of lesion observed depends on the height of the alveolar insertion of the lingual brake:
– high or cervical insertion is associated with a risk of mandibular incisor linguo-version;
– low or apical insertion is associated with a risk of mandibular incisor vestibulo-version;
– a sub-apical insertion is associated with a risk of mandibular recoil.

Ankyloglossia can prevent the posterior part of the back of the tongue from resting on the soft palate, thus compromising the physiological closure of the oropharynx necessary for nasal breathing and promoting the development of oral breathing. Ankyloglossia will cause functional disturbances directly related to postural changes as well as others generated by altered sensory signals. The earlier the intervention, the less growth will be affected.

Ventilation is oral and associated with a more anterior lingual posture, to clear the ABV. The presence of a too short brake will furthermore hinder the activity of the genioglossus, the "safety muscle". A ventilatory dysfunctional pattern has developed, altering the architecture of craniofacial growth.

KL: The concept behind the role of ankyloglossia in sleep is that ankyloglossia contributes

to a reduction in the mobility of the tongue and the muscular force it can apply to the palate, thus reducing the possibility of its development. Although this explanation of the involvement of a short lingual frenulum in the aetiopathogeny of airway collapse may seem logical to many, I would like to reiterate that there is currently no data to support it. We must be very careful when advocating surgery to release the lingual frenulum.

I believe that myofunctional therapy plays a role in improving the muscle strength of the tongue, but again we have too little data. In my practice, I ask patients to be assessed first by an orthophonist to check the strength of their tongue and the possible range of movement. I only agree to operate in cases where I feel I can improve the ankyloglossia and if the patient agrees to undergo myofunctional therapy.

PA: *Frenotomy is a low-risk procedure and is likely to be beneficial if the patient is carefully selected*[180]*. You have studied the effectiveness and reliability of instruments for assessing lingual mobility restrictions*[185]*. What were your findings? Which screening tool do you recommend for use and can you describe the scoring scale you proposed?*

CG, MH-A, Y-SH, KL: The objectives of this study were to evaluate the usefulness of existing instruments for the assessment of restricted tongue mobility, to describe normal and abnormal ranges of tongue mobility and to provide evidence for a reliable and effective measure of tongue mobility. We have shown that the maximum interincisal mouth opening depends on age and size and that the mouth opening with the tip of the tongue at the maxillary retroincisal papillae depends on the maximum interincisal mouth opening. Difference between the two previous measures, the deficit in the amplitude of tongue movements is the only independent measure of tongue mobility that is directly associated with restrictions in lingual function.

We proposed the use of the deficit in the amplitude of tongue movements as an initial screening tool to assess lingual mobility restrictions. Functional ankyloglossia can thus be defined and the effects of treatment objectively monitored using the proposed scoring scale: grade 1: tongue range of motion >80%; grade 2: tongue range of motion between 50-80%; grade 3: tongue range of motion <50%; grade 4: tongue range of motion <25%.

MH-A: The Kotlow technique appears to be the simplest to use. He recommends measuring the length of the frenulum from its insertion in the base of the tongue to its termination near the tip with the Boley gauge. According to the value found, he classifies the ankyloglossia from acceptable (greater than 16mm) to severe (less than 3mm).

PA: *If a frenotomy has not been performed in the infant, a lingual frenectomy may be performed at a later stage. Whatever the surgical modalities, it should be accompanied by lingual physiotherapy exercises to prevent recurrence, the rate of which has been estimated at 15%*[95]*. What exercises and what myofunctional therapy schedule do you recommend?*

CG, MH-A, Y-SH, KL: Recurrence has everything to do with how the operation is performed and whether the patient undergoes myofunctional therapy afterwards. Care must be taken to ensure that the surgical technique is not too aggressive and does not cause a lot of scarring.

3.3. Agenesis and dental extractions

PA: *Numerous studies*[8,121,132,142,169,170,176] *have reported alterations in craniofacial morphology observed in association with dental agenesis. These alterations could lead to decreased development and risk of upper airway collapse. You have studied the potential association between dental agenesis, early extraction of deficient teeth and the development of OSA in children*[39]*. Can you explain how you have shown that the absence of these teeth can lead to a reduction in nasal airflow?*

CG, MH-A, Y-SH, KL: To investigate the potential association between dental agenesis or early dental extractions and the presence of obstructive sleep apnoea (OSA), we examined clinical data, polysomnographic sleep studies and orthodontic imaging studies in children with dental agenesis or early extraction of permanent teeth in the previous five years and compared their results with those of children with normal dental development but adenoids and OSA symptoms. All children with agenesis or early extraction of permanent teeth, with at least two missing permanent teeth, had

complaints and clinical signs suggestive of OSA. In these children, advancing age was associated with the presence of a higher AHI.

We concluded that alveolar bone growth depends on the presence of teeth. Children with permanent teeth missing due to congenital agenesis or permanent tooth extraction had a smaller oral cavity, known to predispose to upper airway collapse during sleep, and had OSA diagnosed at a later age. We pointed out that due to the initial low-grade symptomatology, sleep-disordered breathing may go untreated for a prolonged period of time, with progressive worsening of symptoms over time.

PA: *Another of your publications[39] shows that the search for sleep-disordered breathing should be a constant concern in young children with agenesis. What are your recommendations in terms of family history, orthodontic treatment plan and goals?*

CG, MH-A, Y-SH, KL: The results of our studies show that the search for SRT should be an important concern for clinicians when faced with a young child with missing permanent teeth. Also, when SDB is present in a child, the history should address the family history of missing teeth and It is important to include the missing teeth (their location and number) in the clinical investigation.

We have often observed that children with congenital dental agenesis are hardly ever referred to a sleep centre immediately, and their parents are often reluctant to perform a sleep assessment that they do not perceive as necessary. As a result, referral to a sleep centre is often delayed and polysomnography is frequently only performed when sleep-related symptoms appear or are recognized.

Alteration of normal orofacial development may vary depending on the number of missing teeth, the age of the individual and the impact of the changes on the facial muscles. These changes may have a gradual impact on the width and stability of the upper airway during sleep and symptoms may only be noted by parents after a variable time interval.

Clinically, it is important for odontologists to be aware of the potential risk of developing OSA due to the absence of permanent teeth and to favour treatment approaches that avoid early extraction of permanent teeth.

PA: *In your video interview with Dr. Mike Milligan[73], you said about the use of dental avulsions in orthodontics: "we are very very against that" and you recalled that dental agenesis and early extraction of permanent teeth can lead to a reduction in nasal airflow. In an adolescent at risk of OSA, it does seem preferable to favour mandibular advancement orthognathic surgery rather than requesting avulsion of maxillary premolars to camouflage a class II malocclusion with mandibular retrognathia[6,75].*

In the case of macrodontia without associated sagittal or transverse anomalies, in adolescents or adults, do you think that the indication for extractions remains pertinal when their purpose is to avoid pushing the teeth out of the bone volumes and thus exposing the patient to an increased risk of gingival dehiscence, or to avoid imposing on the patient a maxillary disjunction associated with symphyseal distraction in order to avoid these extractions?

CG, M.-A, Y-SH, KL: Yes, after dental and skeletal diagnosis, the correction of tooth-arch disharmony (TAD) by macrodontia often involves a decision to extract permanent teeth. This is a therapeutic imperative in orthodontics when periodontal health and the durability of the treatment outcome are at stake.

We would like to point out that the need to intervene as early as possible in the case of OSDB implies that the treatment (maxillary disjunction, mandibular advancement orthosis or activator) should take place well before the age of the actual alignment treatment, including the correction of the DDA.

Yes, in the case of a class II malocclusion with mandibular retrognathia in the adolescent, if the therapeutic motivation is the management of a proven OSDB, it is clear that the surgical indication will be given. The worst case scenario would be a useless or even deleterious compromise of alignment therapy.

KL: Sometimes the extraction of permanent teeth is indeed necessary. However, one should

always try to expand rather than remove teeth. The problem is that most of the jaw expansion techniques used only push the teeth out by vestibulizing them, rather than actually expanding the jawbone. I have been able to develop an endoscopically assisted surgical expansion procedure in adults[114] as well as children to actually expand the naso-maxillary complex.

PA: *Thank you Kasey for this important clarification, which we will discuss in more detail below.*

3.4. Orofacial hypotonia

PA: *You have written that paediatric obstructive sleep apnoea in non-obese children is an orofacial growth disorder[40,78]. Can you remind us of the evidence that orofacial hypotonia[48] is a fundamental component in the development of anatomical abnormalities leading to abnormal breathing during sleep, and that there is a continuous interaction between orofacial muscle tone, maxillomandibular growth and the development of sleep-disordered breathing?*

CG, MH-A, Y-SH, KL: Figures 2 and 3 summarize the interrelationships between orofacial muscle tone, maxillomandibular growth and the development of sleep-disordered breathing. We have shown that in children preterm infants, certain generalized muscle disorders and factors such as short lingual frenulum and dental agenesis, which impact on orofacial growth and maxillomandibular impairment, will increase "hypotonia", the risk of a "hypoactive" condition.

The "mouth breathing" and the "narrow hard palate".

The development of the oral cavity begins around the second month of pregnancy. Fetal ultrasound has provided us with a great deal of knowledge and has shown fetal functions such as swallowing amniotic fluid, sucking, and certain reflexes involved in the development of the oral cavity. Other early life functions such as nasal breathing, sucking, swallowing, chewing and speaking are also related to orofacial development. Therefore, abnormalities in these functions increase the risk of abnormal development of the bony structures supporting the upper airway, leading to an increased risk of upper airway collapse during sleep.

The tongue plays a major role in the hypotony of the orofacial musculature. The early installation of the vicious circle of dysfunction/hypotonia will impact on growth and create the bed for future neuropathy.

PA: *For almost three decades[25], orofacial rehabilitation has been an integral part of orthodontic treatment, with the main objective of restoring optimal nasal ventilation[171,172]. At the 21st Congress of the European Sleep Research Society in September 2012 in Paris, two of your oral presentations[47,48] presented the results of a retrospective study on the efficacy of myofunctional rehabilitation in preventing relapse of OSA in children, and on hypotonia as a risk factor for recurrence of OSA at puberty. Can you report on your findings and the rehabilitation modalities that were implemented?*

CG, MH-A, Y-SH, KL: Limited data suggest that pubertal development may lead to recurrence of sleep-disordered breathing (SDB) despite prior curative adenotonsillectomy. Long-term myofunctional assessment in our retrospective cohort study[49] showed that after adenotonsillectomy, subjects who did not undergo orofacial myofunctional rehabilitation (OMR) had abnormal orofacial muscle tone when awake. They also had a recurrence of symptoms with a mean apnoea-hypopnoea index (AHI) of 5.3 ± 1.5 and a mean minimum oxygen saturation of 91 ± 1.8%, whereas the subjects who underwent OMR were symptom-free and had a normal functional status. Myofunctional rehabilitation consisted of strengthening the tongue and orofacial muscles by learning to reposition the muscles to the appropriate position and to breathe continuously through the nose.

3.5. Adolescent OSA

PA: *As early as 2007[46], you identified the symptomatology of adolescent OSA. Transition between childhood and adult OSA, adolescent OSA is predominantly type 291. Can you present the main pathophysiological, semiological and therapeutic characteristics of this condition?*

CG, MH-A, Y-SH, KL: Little research has been done on the specifics of OSA in adolescents. It is usually associated with overweight and obesity. It is indeed a type 2 OSA that adolescents suffer from, often without significant adenoidal-tonsillar hyper-

trophy. They have excessive daytime sleepiness and psychological disorders, and suffer from metabolic and cardiovascular complications.

Changes in sex hormone production, muscle hypertrophy, craniofacial skeletal maturation and obesity all contribute to the increased risk of developing OSA. The treatment of adolescent OSA is the same as for paediatric OSA, depending on the underlying causes.

3.6. Attention deficit disorder with or without hyperactivity

PA: *OSA may contribute to the symptomology of attention deficit hyperactivity disorder (ADHD) and treatment of OSA appears to have positive effects on ADHD symptoms[26,76,81,88,182]. You recommend that assessment of sleep disturbance be considered in all patients with ADHD, particularly before the start of medication[76]. What advice would you give to orthodontists who are in the front line of communicating this recommendation to their patients' families?*

CG, MH-A, Y-SH, KL: We have shown that OSA has a negative systemic impact. Not only does it cause cardiovascular dysfunction, but it also has clear effects on alertness, learning, memory, academic achievement, growth, abnormal behaviours suggestive of Attention Deficit Hyperactivity Disorder (ADHD), and mood disorders, such as depression and parasomnias, such as enuresis, sleepwalking and night terrors.

We also found[76] that inattention, neurocognitive function and learning problems improved after treatment of paediatric OSA. Therefore, if outpatients present with symptoms of inattention, hyperactivity, learning and emotional problems, daytime sleepiness and open-mouthed breathing during the day and snoring, enuresis and restless sleep at night, it is recommended to request a PSG and confirm the likely diagnosis of OSA.

The diagnosis of ADHD requires a consultation with a child psychiatrist and is only established following a very precise semiological approach. It is estimated that about 2% of ADHD has a ventilatory origin. Orthodontists have the privilege of seeing children at a very young age and it is useful to include some questions about sleep quality and behaviour in the initial consultation.

PA: *You advocate that OSA should be treated as early as possible to reduce the incidence of ADHD in children[81,181]. With this in mind, what do you think is the ideal age for a first consultation with an orthodontist?*

CG, MH-A, Y-SH, KL: We have suggested that the earlier OSDB is treated, the better the outcome. Treatment can start with orofacial myofunctional therapy implemented early in the baby's life. Usually, preschool children have a dental examination and if the dental surgeon or orthodontist observes the above symptoms, they should refer to a paediatric physician for polysomnography and treatment.

3.7. Snoring

PA: *In a 2004 commentary in Chest entitled "Does benign "primary snoring" ever exist in children? "[54] you stated that chronic snoring always has deleterious health consequences, including a possible increase in cardiovascular risk in adulthood[126], and that you had never observed a child with only primary snoring, provided the examination was appropriate[125]. Can you tell us what examinations should be carried out systematically in the case of a snoring child, including the examination of the craniofacial skeletal pattern?*

CG, MH-A, Y-SH, KL: From the point of view of preventive medicine, we believe that chronic snoring in children is not normal, and that snoring is a warning sign for their health. If children have open mouth breathing, adenoid face, mandibular retrognathia, narrow hard palate, nasal obstruction, open mandibular plane angle, increased facial height, we need to be alert. It should also be borne in mind that the analysis of the facial pattern of a snoring child is important but that this pattern does not always follow a precise type. It is the history that will guide our examination.

PA: *Together with Jacques Talmant, et al.[172], we have pointed out that structural changes secondary to the vibratory trauma caused by snoring can affect each component of the pharyngeal structures and contribute to the collapsibility of this segment of the airway. A prospective study[120] showed that in a group of 29 untreated men with sleepiness and snoring, the number of cases of OSA increased over 10 years from 4 to 13 ($p < 0.01$). Another[9] showed that patients with primary snoring or mild obstructive sleep apnoea showed a similar increase in the apnoea/hypopnoea index over time, which was*

mainly dependent on weight gain and, to a lesser extent, time. Have you observed any diagnostic and therapeutic evolution in the medical world, and particularly in orthodontists, with regard to snoring, which should never be considered a priori benign and should be systematically investigated?

CG, MH-A, Y-SH, KL: We believe that any flow limitation found on a sleep polygraph (SP) or PSG examination in children should be taken into account.

MH-A: In daily clinical practice, we play a screening role and refer the child or adolescent to the ENT specialist or paediatrician if necessary. Thanks to the French Society of Dental Sleep Medicine (SFMDS), awareness is evolving and inter-specialty links are improving. The double special issue of L'Orthodontie Française published in december 2019 and the multidisciplinary days co-organised by the Société Française d'Orthopédie Dento-Faciale (SFODF) and the SFMDS bear witness to this evolution.

PA: *Your recent prospective cohort study[128] analysed the relationship between snore sound energy (SSE) and the severity of obstructive sleep apnoea, as well as changes in SSE after adenotonsillectomy and predictors of surgical success in children with OSAS. Can you share your conclusions and perspectives with us?*

CG, MH-A, Y-SH, KL: We enrolled thirty-two children with OSA with apnea-hypopnea index ≥ 5 or apnea-hypopnea index ≥ 1.5 with comorbidities associated with OSA. All participants had undergone snore sound analysis, polysomnography and adenotonsillectomy. Snore acoustic energy and apnoea-hypopnoea index were assessed at baseline and six months after adenotonsillectomy. Surgical success was defined as a postoperative apnoea-hypopnoea index < 1.5. We showed that the snore sound energy (SSE) of 801-1000 Hz < 8.5 dB predicted significant surgical success. Our results suggest the potential usefulness of 801-1,000 Hz SSE as a potential biomarker for screening for severe OSA, predicting surgical success and evaluating therapeutic outcomes.

PA: *You examined the effects of cervical position[100] on obstructive sleep apnoea syndrome using a custom-designed cervical pillow to promote neck extension. What changes were observed according to the severity of OSA? As head posture has a marked effect on upper airway collapse, can our patients expect a therapeutic gain from the future development of such devices?*

CG, MH-A, Y-SH, KL: Our study on the effects of neck positioning on OSA using a neck pillow showed that subjects with mild OSA had a non-significant improvement in the severity of their snoring and a significant improvement in their respiratory disorder index with the neck pillow, while subjects with moderate OSA showed no improvement in these parameters. Subjects with severe OSA showed a slight improvement in some measures of their abnormal respiratory events over the experimental period. The usefulness of this positional treatment therefore appears to be limited at present.

PA: *You have shown the effectiveness of functional myotherapy on snoring in adults[17]. How is it prescribed for snoring children?*

Y-SH: In Taiwan, we have already conducted a few studies, two of which were published this year[29,83], showing, with PSG and cephalometric analysis of profile teleradiographs, the improvement of orofacial myofunctional therapy and passive myofunctional therapy (with the lingual stimulation ball brace developed by Michèle Hervy-Auboiron) in the treatment of paediatric OSA. Therefore, in our sleep centre, if non-obese children have snoring and do not have enlarged tonsils and adenoids, or after adenotonsillectomy, we will systematically implement orofacial myofunctional therapy or passive myofunctional therapy in them.

PA: *You have devoted several publications[60,147,159,160,161] to the surgical treatment of snoring. What is the current state of knowledge on this subject?*

KL: It is important to note that the treatments for snoring and OSA are essentially the same. I don't think there is such a thing as "simple snoring". Someone with "simple snoring" is a patient whose PSG has not been read and analyzed by someone with sufficient expertise to detect flow limitations, etc.

I always recommend non-invasive treatment first, such as a mandibular advancement orthosis, but only after informing patients of the risk of adverse effects on their occlusion.

The improvement in nasal breathing that can be seen is always important. I perform many endoscopically assisted surgical naso-maxillary expansions to treat snoring and OSA.

3.8. Restoration of nasal ventilation

PA: *You have shown that oral ventilation induces "disuse" of nasal breathing with changes in proprioception, posture and loss of use of the nose[103]. Chronic oral breathing, which is an important clinical marker of dysfunction of the orofacial musculature and may be associated with restricted palate growth[44,66,131], must be eliminated[65]. To restore nasal breathing during wakefulness and sleep, which you feel is the only valid criterion in the treatment of OSA[65], you recommend the use of myofunctional therapy[17,47,49,78,83] and passive myofunctional therapy with the Michèle Hervy-Auboiron device[77,103,119]. What do you think about the use of prefabricated myofunctional splints[105,106]?*

CG, MH-A, Y-SH, KL: Our studies have shown that chronic open mouth breathing is an important clinical marker of orofacial muscle dysfunction. Therefore, orofacial myofunctional therapy and passive myofacial therapy with the Michèle Hervy-Auboiron device are ways to achieve this goal of nasal breathing during wakefulness and sleep. Our studies have shown that such behavioural changes can be achieved by daily re-education exercises (orofacial myofunctional exercises) and by natural reflex action during sleep (Michèle Hervy-Auboiron device). It should be noted that the prerequisite for any re-education is the recovery of the vacuity of the VAS, with a possible indication of tonsillectomy and/or adenoidectomy upstream if necessary.

Assisting orofacial rehabilitation by wearing a splint requires, as with wearing a brace, informing patients of the risk of adverse effects on their occlusion. We await the publication of studies of sufficiently high methodological quality, with at least one control group, before expressing an opinion on the value of using these prefabricated devices for the treatment of paediatric obstructive sleep apnoea.

3.9. Therapeutic education

PA: *Sleep education programmes, especially in schools[12,94,141], are one way of informing people who suffer from sleep insufficiency. It should be noted that patient education, including therapeutic education[34], is similar to the approaches orthodontists use in daily clinical practice (awareness training[104], ortho-functional re-education[5], etc.) to develop adherence and optimize orofacial function in their patients, including ventilatory function[172]. What advice would you give to orthodontists to further help their patients achieve the compelling goal of restoring day and night nasal ventilation[65]?*

CG, MH-A, Y-SH, KL: Compliance of their patients can probably be improved by providing well-founded information on the health benefits of myofunctional rehabilitation and the risks involved if continuous nasal breathing during wakefulness and sleep is not restored.

3.10. Adenotonsillectomy

PA: *As the pathophysiological knowledge of OSA has evolved, so has the management of the infant, from tracheostomy, to continuous positive airway pressure, to adenotonsillectomy combined with orthodontic treatment and orofacial myofunctional rehabilitation[27]. Can you provide our readers with an overview of the key steps underlying this therapeutic evolution?*

CG, MH-A, Y-SH, KL: We have shown that removal of the tonsils and vegetations is not always followed by long-term therapeutic success[58] in paediatric OSAS. This recurrence called for a broader therapeutic arsenal, continuous positive airway pressure (CPAP) and maxillofacial surgery in the most severe cases. Then, the possibilities offered by orthodontics for the treatment of SRT opened a new therapeutic avenue. Rapid maxillary expansion, bimaxillary distraction and orofacial functional myotherapy were incorporated into the management of OSAS in children.

KL: Therapeutic advances involve many factors. Obviously, it's about reducing invasiveness and improving the effectiveness of therapeutic proposals. No one will advocate a tracheostomy today and we now understand that the use of CPAP in children often results in midface impairment. I think the indication for an adenotonsillectomy is

relevant (if the lymphoid tissue is enlarged) and naso-maxillary expansion with exercise can help most patients, but often the response is incomplete. I tell patients that there is no miracle cure and that we can only improve...

PA: *You[46,56,58,80] and other authors[101,156,162,167,174,175] have reported cases of recurrence of obstructive sleep apnoea in children operated on by adenotonsillectomy, despite the disappearance of symptoms and the normalisation of polygraphic tests observed after the operation. You have emphasised the need for a wider range of treatment than adenotonsillectomy, which you mentioned in your previous answer and which we would now like to discuss with you in more detail.*

CG, MH-A, Y-SH, KL: It will be a pleasure. The recurrence of paediatric OSA cases that we published was associated with changes in orofacial growth induced by oronasal dysfunction with the creation of negative feedback loops. The abnormal orofacial growth, induced by the ventilatory dysfunction, resulted in reduced development of the upper airways with an increased risk of collapse during sleep.

KL: I believe that endoscopically assisted surgical nasomaxillary expansion is superior to adenotonsillectomy in many children.

PA: *For adolescents with recurrence of symptoms after adenotonsillectomy, you have proposed the use of continuous positive airway pressure (CPAP)[59]. You have published extensively on CPAP[20,37,87,99,139,148,149,152] and you were the first[115] to explain the possible impact of the interface on the growth of the facial mass of the child[36,158] or even on the teeth of a 64 year old adult[145]? In addition to careful monitoring, what precautions can be taken to prevent this possible iatrogenic effect?*

CG, MH-A, Y-SH, KL: Continuous positive airway pressure (CPAP) for the treatment of obstructive sleep apnoea in children is a common treatment that can alter the normal growth of the facial skeleton due to the pressure exerted by the mask. This adverse effect calls for increased collaboration between sleep physicians and orthodontists to monitor mid-face growth during CPAP treatment.

MH-A: When CPAP is indispensable, temporarily or not, I have sometimes "cobbled together" a protraction mask on the face mask with support from a splint or an intraoral double-arch. The objective of this original association between the protraction mask and the face mask is to prevent the pressure exerted by the mask from maintaining or even aggravating a particularly deleterious retromaxillia.

PA: *For adolescents who become symptomatic again after adenotonsillectomy, you have shown that upper airway obstruction may be partially related to craniofacial risk factors[58,78]. You advocate that surgical treatment[56,153] should also aim to widen the airways and not just treat inflammation or infection of the lymphoid tissue. What types of interventions do you favour?*

CG, MH-A, Y-SH, KL: Absolutely, when airway enlargement is required, treatment of lymphoid tissue inflammation or infection alone may be insufficient to resolve residual symptoms after adenotonsillectomy. In such cases, further treatment, including collaboration with orthodontists to improve craniofacial risk factors, should be considered. In addition to allergy treatment, endoscopically assisted surgical naso-maxillary expansion may be offered.

PA: *The prevalence of allergic rhinitis in children with OSA or SRT is particularly high and children with SRT have a higher incidence of allergic rhinitis than those without SRT[22]. In addition, children with allergic rhinitis have an increased risk of persistent sleep-disordered breathing[92,102] after adenotonsillectomy. What specific follow-up do you recommend for them?*

CG, MH-A, Y-SH, KL: We recommend that children with allergic rhinitis undergo allergy treatment, such as desensitisation, whether or not they have had an adenotonsillectomy. In children with OSA who have had an adenotonsillectomy, the procedure should be followed by polysomnography and the children should do regular orofacial myofunctional exercises. In addition, oral breathing and craniofacial development, body weight and allergic rhinitis should be systematically monitored. If necessary, orthodontic treatment may be recommended.

PA: *You have published a long-term study[80] with systematic postoperative follow-up of adenotonsillectomies. You have shown that persistence and recurrence of obstructive sleep apnoea syndrome in children, with slow worsening of the apnoea-hypopnoea index (AHI), can frequently occur within three years, even in the context of a short-term postoperative benefit. Can you explain to our readers when and how you prescribe myofunctional rehabilitation[49] to help these patients achieve the necessary goal of restoring day and night nasal ventilation[65,103]?*

CG, MH-A, Y-SH, KL: In our study, we showed that adenotonsillectomy results in significant improvement in the apnea-hyporesia index, although usually with incomplete resolution, and we observed worsening over time in 68% of our cases. This high rate of recurrence requires routine orofacial myofunctional treatment before and after adenotonsillectomy. The exercise prescription varies from five minutes of exercise twice a day, four days a week for two months to ten minutes of exercise three to five times a day for three months.

3.11. Functional myotherapy

PA: *Functional myotherapy sessions are an aid not only to the treatment of sleep-disordered breathing[14,49,79] but also to the understanding of epigenetic phenomena in oro-naso-facial development, which play an important role in the genesis of sleep-disordered breathing in children[27]. What functional myotherapy modalities and exercises do you recommend?*

CG, MH-A, Y-SH, KL: Our latest study[50], which has just been accepted for publication by the journal Sleep, shows that the tongue is an essential organ with many receptors. It enables proprioception in the fetus and newborn and this sensory system is further refined in adolescence and adulthood. The tongue is the second largest sensory system in the body, after the tactile sensory system. The numerous receptors on its surface, especially the tactile mechanoreceptors, allow the recognition of shapes and surfaces of objects and play an important role in defending the tongue against biting, in eating, drinking and speaking. Therefore, it is essential that orofacial myofunctional rehabilitation includes lingual exercises such as:

1. Pull the tongue as far out of the mouth as possible.
2. With tongue out of mouth, touch right cheek.
3. With tongue out of mouth, touch left cheek.
4. With your tongue out of your mouth, try to touch the tip of your nose.
5. Place the tip of the tongue in the middle of the palate.
6. Place the tongue on the crowns of the upper teeth.
7. Stretch and place the tongue between the teeth and hold it there by squeezing gently.

These simple exercises are systematically prescribed to the small patients in our sleep centres.

PA: *In addition to the contribution of active orofacial myofunctional rehabilitation, you have also studied and shown the value of using passive myofunctional rehabilitation[30,77,119]. Can you share the results of your studies on this subject with our readers?*

CG, MH-A, Y-SH, KL: Yes, of course. In addition to the publications mentioned, we conducted a study[29], to be published at the end of the year, which aimed to evaluate the effects of one year of passive orofacial myofunctional rehabilitation (POMR) on craniofacial and airway morphology and quality of life in children with obstructive sleep apnea.

We showed that the apnoea-hypopnoea index (AHI), REM AHI, number of hypopnoeas and number of desaturations in the treatment group (with Michèle Hervy-Auboiron's oral tongue ball device) decreased significantly at PSG. Regarding airway morphology, the inter-group comparison showed that OPha-Ophp (distance between the anterior and posterior surfaces of the oropharynx) increased significantly in the treatment group. Regarding quality of life and clinical symptoms, the intergroup comparison showed statistically significant improvements in the treatment group (based on the OSA-18 questionnaire) for the following items: loud snoring, dysphagia, mood swings, discipline problems, waking difficulties, total score for the emotional distress section and total questionnaire score. We concluded that one year of OPMR using an oral device with a tongue ball improves AHI, nasal breathing during sleep, mandibular linear growth (Co-Gn and N-Me), airway morphology (OPha-Ophp) and clinical symptoms in children with OSA.

PA: *Michèle, can you describe the original device[30,77,119] that you created for these studies? What are the therapeutic concept, indications, wearing patterns and therapeutic effects?*

MH-A: The concept was born from a thought initiated by Alain Lautrou during our studies at the university diploma in occlusodontics: would it be possible to use a more functional orthosis to treat OSA?

The main objective of this custom-made one-piece mandibular advancement orthosis (patent number: EP 13753289.1; US14/420499) is to reduce external mechanical forces and increase muscle contribution, or even to rehabilitate.

Thus, Myonyx® would belong to the "tissue born appliances", i.e. the mucosal and non-dental supported thrusters. It is composed of a resin jaw tray fixed by two molar clasps. The mandible is free and only indentations guide the occlusion. This is calculated for an advance of 4-5 mm and a lowering of 3 mm. These values allow, according to Ahlgren and Bendéus[2], to remain within 20% of the muscle stretch or shortening coefficients.

A moving ball target is placed on a resin-embedded bracket located at the alveolar mucosa. The target is placed 2 mm from the lingual mucosa and approximately 3 mm below the gingival margin. When the patient opens his or her mouth, a reflex contraction of the lateral pterygoid occurs, called the Bass avoidance reflex. Pressure from the periodontal sensory receptors in contact with the target also stimulates the lingual propeller muscles. This is a survival mechanism designed to repel any object placed in the mouth; the tongue attempts to get rid of the foreign body.

The aim is to use targeted, appropriate and effective muscle recruitment. Our aim is to use the sensory properties of the tongue to enhance muscle recruitment and tone, while reducing stress on the teeth. While growth promotion is only possible in children, adults benefit from the minimal stress on their teeth that this device provides, in addition to a kind of passive myofunctional rehabilitation.

CG immediately joined the project and led the studies in adults in Europe and Canada and in children in Taiwan.

3.12. Maxillary retraction

PA: *Maxillary protraction devices can increase the size of the upper airway[33,134] and hopefully reduce the risk of OSAS in children with maxillary retrognathia[130]. Maxillary protraction with skeletal anchorage induces a greater skeletal effect than that achieved with facemask protraction[24,31]. You have studied the effects of using bone-anchored maxillary protraction to treat maxillary retrogression, malocclusion and obstructive sleep apnoea in children[151]. What were the findings?*

CG, MH-A, Y-SH, KL: Certainly, maxillary retrognathy creates an upper airway undersize problem that can be ameliorated in children with orthopaedic maxillary protraction, with dental or skeletal anchorage, or subsequent surgical maxillary advancement.

The results of these treatments have been most promising for pharyngeal airway enlargement. The objectives of our pilot study were to evaluate the use of bone-anchored maxillary protraction as a strategy for treating maxillary retrogression, class III malocclusion and obstructive sleep apnea in children.

Our preliminary results showed an improvement in apnoea-hypopnoea index (AHI) and OSA symptoms in the majority of children, as well as an improvement in respiratory and airway parameters with a highly significant change in the posteroanterior position of the maxilla and widening of the nasopharyngeal to oropharyngeal junction, compared to an untreated age- and sex-matched control group. The results depended on the age of treatment initiation and the patient's compliance with treatment.

3.13. Functional devices

PA: *Clinical studies show that functional device treatments increase the volume of the oropharyngeal airway and the anteroposterior position of the hyoid bone in growing patients with class II malocclusion[89,157,177,179]. They could thus reduce the potential risk of OSA in growing patients, as shown by two recent systematic reviews[86,183], although the latest Cochrane systematic review[23] could not conclude on the efficacy, or lack of it, of using functional devices for the treatment of obstructive sleep apnoea in children. What is your opinion?*

CG, MH-A, Y-SH, KL: Prospective studies on young growing patients are very difficult to implement because of possible ethical constraints. The research we have conducted in Taiwan is recognised as being methodologically rigorous. It shows that the treatment plan must be individualised on a case-by-case basis and that it is desirable to do everything possible to ensure that growth is expressed harmoniously and without constraints. The promise of functional therapy exists for OSAS in children. In the current state of knowledge, this is a real option. Primum non nocere.

3.14. Maxillary or bimaxillary expansion

PA: *You have studied the role of rapid maxillary expansion in the management of OSAS in children[16,143,144]. Can you give us the key points?*

KL: The key to naso-maxillary expansion is not expansion of the teeth or the socket! The goal is to expand the nasal airway. One should be cautious in thinking that the new expansion techniques with skeletal anchorage, such as MARPE (mini-screw-assisted rapid palatal expander) or DOME (Distraction osteogenesis maxillary expansion) are different, because they are not. The expansion model is the same as that of the traditional methods and all the data are available in the literature. The key to therapeutic effectiveness is to perform the expansion in the young subject. The average age of maxillary expansion in the meta-analysis you quoted[16] was 7.6 years.

PA: *Bucci, et al.[13] concluded their review of systematic reviews by stating that while rapid maxillary expansion allows for a significant increase in nasal cavity volume in the short and long term, maxillary expansion cannot currently be indicated when the sole objective is upper airway improvement and must therefore be supported by an orthodontic indication. Do you agree with their conclusion?*

KL: I strongly disagree, but I understand the reasoning behind their recommendation. You're trying to get an expansion of the nasal airway, but you're creating an over-expansion of the maxilla and disturbing the dental occlusion.

Therefore, I advocate pure or almost pure skeletal expansion to minimize dental changes. I have just published an article[114] in Sleep Medicine on this endoscopy-assisted surgical expansion technique for adults and hope to publish its application in children soon. This outpatient surgical procedure is designed to expand the maxilla to treat obstructive sleep apnoea. EASE (Endoscopically-assisted surgical expansion) is an outpatient procedure that improves nasal breathing and OSA by enlarging the nasal floor, not in a traditional V-shape, but of the same width from the anterior nasal spine

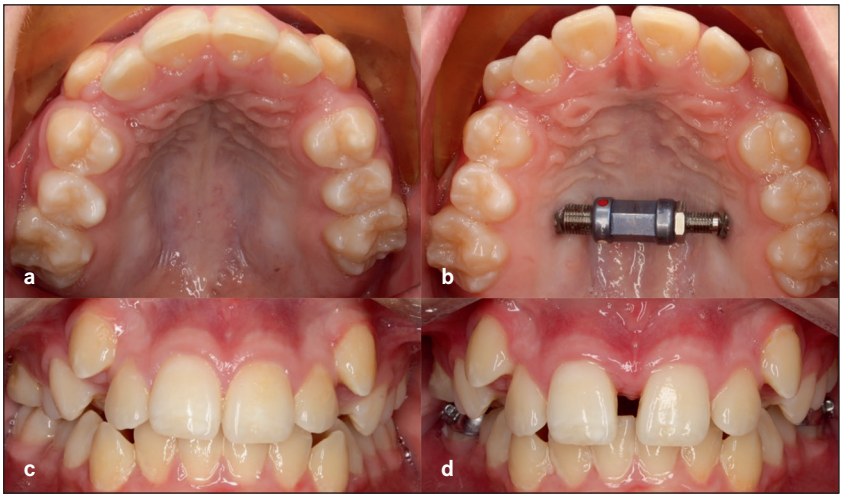


Figure 4

A child with OSA and maxillary dental crowding underwent endoscopically assisted naso-maxillary skeletal surgical expansion. Pre (a and c) and post (b and d) views (note the reduced size of the medial inter-incisal diastema showing the small impact of the skeletal expansion at the dento-alveolar level).

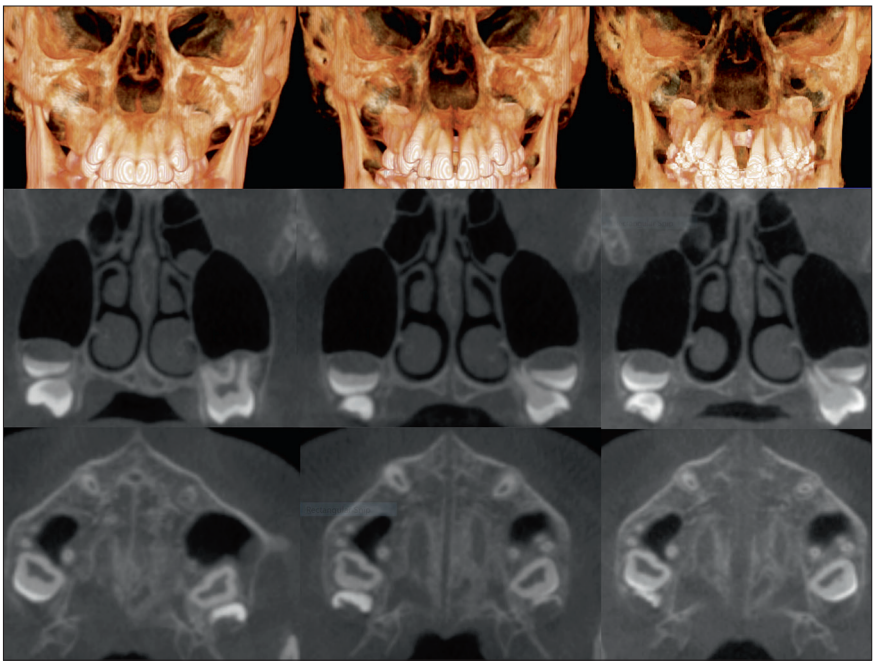


Figure 5

CBCT scans showing the progression of endoscopically assisted surgical expansion with complete separation of the median suture. Note the achievement of posterior expansion with complete separation of the suture between SNA and SNP, in contrast to typical fan expansion where anterior expansion may be excessive.

(ANS) to the posterior nasal spine (PNS) (Figs. 4 and 5). Compared to current surgical approaches for maxillary expansion, this new technique is considerably less invasive and allows airway enlargement with minimal complications.

PA: *You have shown that bimaxillary expansion, using rapid maxillary skeletal expansion and mandibular dentoalveolar expansion, improves the respiratory parameters of some children with OSA[150]. Can you tell us the conclusions of your study and its clinical perspectives?*

CG, MH-A, Y-SH, KL: Yes, the aim of our retrospective study was to evaluate the results of bimaxillary expansion, with rapid maxillary skeletal expansion and mandibular dentoalveolar expansion, as a treatment option for sleep-disordered breathing in children. Our results showed that the majority of children had improved sleep scores and symptoms after bimaxillary expansion. However, in the "mild OSA" group, patients with reduced mandibular plane angle or counterclockwise mandibular growth worsened with bimaxillary expansion, while patients with hourly mandibular growth showed greater improvement. In the severe OSA group, patients with mandibular retrognathia had less improvement in AHI.

PA: *Unlike the maxilla, non-surgical mandibular skeletal expansion is not possible. Only dentoalveolar expansion and the correction of a possible coronolinguoversion of the lateral sectors can be considered, within narrow limits, in order not to expose the patient to therapeutic recurrence[72,122] or gingival dehiscence. As a corollary, these therapeutic limits in the mandible require restricting the amount of maxillary expansion in order to preserve a satisfactory transverse occlusal setting.*

Symphyseal distraction[164] allows surgically assisted skeletal mandibular expansion. The technique of osteogenic distraction applied to mandibular expansion has been proposed[69,168] for the treatment of OSDB. You were the first[55] to study the improvement in sleep-disordered breathing achieved by symphyseal distraction combined with maxillary disjunction or maxillary distraction. What were your findings and what are the indications for this therapeutic approach?

KL: Christian and I did it many years ago, in 2004, and I don't do it now because the key to expansion

is really to widen the nose, which is achieved by my endoscopically assisted surgical naso-maxillary expansion technique[114].

3.15. Other surgical procedures

PA: *You have devoted many articles to the surgical treatment of OSA, of which I am only referencing the most recent ones*[15,18,19,21,108-114,116-118,123,124,133,154,155,173,186]. *What are the short- and long-term results and current indications of these various procedures?*

KL: Out of all the interventions you mentioned, I have selected the most effective ones and now I only do a few for children and adults. They give quite good results in most patients and, of course, patient selection is the key to therapeutic success.

I would mention, adenotonsillectomy in children if indicated, endoscopically assisted naso-maxillary expansion, nasal surgery and maxillomandibular advancement in adolescents if OSA is persistent.

In adults, I perform pharyngoplasty, if and only if the tonsils are large, nasal surgery (Fig. 6), endoscopy-assisted surgical naso-maxillary expansion and maxillo-mandibular advancement (Fig. 7).

4. Conclusion

PA: *In 2017, you wrote that "Many doors have been opened in a few years thanks to the study of OSA, but many questions still remain unanswered"*[27]. *We thank the four of you for holding these doors wide open to offer the readers of French Orthodontics a synthesis of some*

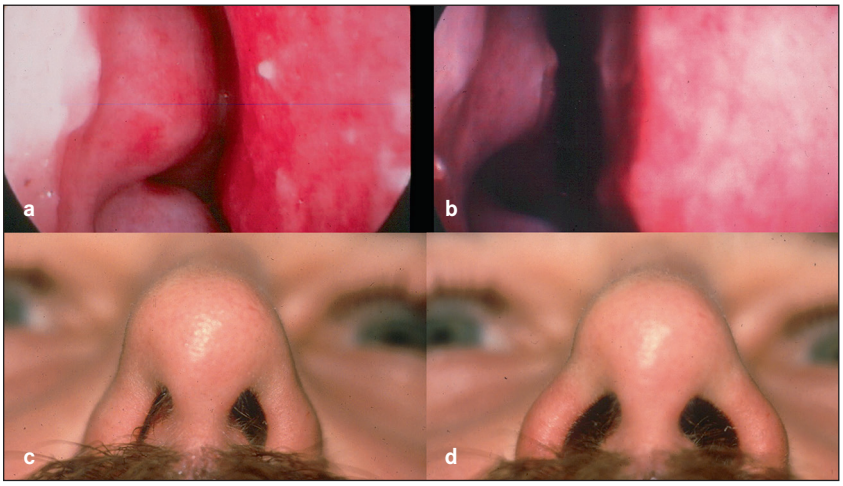


Figure 6
Nasal surgery and nasal valve repair. Before (a and c) and after (b and d) surgery.

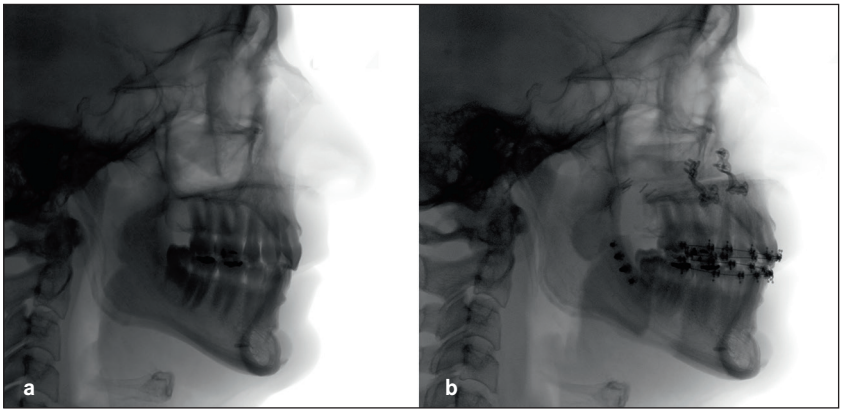


Figure 7
Profile teleradiographs, before (a) and after (b) maxillomandibular advancement surgery. Note the significant advancement while minimizing the use of titanium plates and screws, sometimes used in excess by some surgeons.

of the key elements of the relationship between sleep medicine and orthodontics.

CG, MH-A, Y-S.H, KL: We were pleased to be able to participate in this collegial interview, whose format allowed us to present the current state of the interrelationship between sleep medicine and orthodontics, while also giving us the opportunity to express the nuances of our individual views.

M.H-A: The main message to be retained from the work of CG is that everything is treated in childhood in terms of OSA. It is at this price that we can hope to avoid the irreversible adult neuropathy. It is clear that Jacques Talmant's work was a precursor.

Orthodontic and orthopaedic treatment is an essential part of the treatment of children's OSDB with a major functional focus. The world's most famous sleep therapist has not only given our speciality a noble status, but has also reaffirmed its mission.

Links of interest

The authors declare that they have no links of interest regarding the data published in this article.

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Original article

Surgical and non-surgical maxillary expansion: expansion patterns, complications and failures

Kasey LI[1*], Christian GUILLEMINAULT[2]

[1] Sleep Apnea Surgery Center, 1900 University Avenue, Suite 105, East Palo Alto, CA, USA
[2] Deceased. Sleep Medicine Division, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA

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SARPE / DOME / MARPE / MSE / ALF / EASE / AGGA / DNA / OSA / Airway / Maxillary expansion / Nasomaxillary expansion

ABSTRACT – Objective: *The focus of this report was to analyze the pattern of maxillary expansion and complications in patients following surgical and non-surgical maxillary expansion presented for evaluation and second opinion.* **Materials and Methods:** *During a 30-months period, 28 patients presented for second opinion following maxillary expansion performed elsewhere. The indication for treatment was obstructive sleep apnea (OSA). All patients reported a lack of symptomatic improvements and problems associated with the treatment. Clinical examination with pre- and post-expansion cone beam computed tomography (CBCT), and treatment photographs were analyzed.* **Results:** *Complete clinical records and CBCT were available in 22 patients for analysis. Six patients had undergone surgical expansion with distraction osteogenesis maxillary expansion (DOME), and 16 patients had undergone a variety of non-surgical expansion with different appliances. All the DOME patients had anterior nasal spine (ANS) separation without posterior nasal spine (PNS) separation. Diastema ranging between 10-16 mm was noted in the DOME patients, and the ratio of anterior diastema to ANS separation was between 2:1 to 3:1. Bone defects existed between the central incisors at 18 months or beyond following DOME in all the patients despite bone grafting attempts in four patients. Anterior gingival recession occurred in two patients and four incisor teeth required endodontic therapy with long-term guarded prognosis. Sixteen patients underwent non-surgical maxillary expansion with four different appliances, including anterior growth guidance appliance (AGGA), daytime-nighttime appliance (DNA), advanced lightwire functionals appliance (ALF), and mini-screw assisted rapid palatal expansion (MARPE). The midpalatal suture did not separate in any of the 16 patients, and the expansion pattern was purely dental and dentoalveolar in nature. Lateral dental tipping, thinning of the labial/buccal alveolar bone with gingival recession were noted in 10 patients. Significant mobility of the maxillary anterior teeth due to vertical and horizontal bone loss was noted in the five patients that underwent AGGA treatment.* **Conclusions:** *Different maxillary expansion methods are currently being performed with varying outcomes. Critical analyses of these methods are needed to determine their impact and whether the desired outcomes are achieved.*

* Correspondance : drli@sleepapneasurgery.com

1. Introduction

Since the report of improved Obstructive Sleep Apnea (OSA) following maxillary expansion in 1998[5], the use of surgical and non-surgical maxillary expansion for the treatment of OSA has become increasingly popular. However, the results of different maxillary expansion methods seem to vary greatly, and some expansion methods have little or no published outcomes data. The authors aimed to analyze the pattern of maxillary expansion and complication in patients who sought a second opinion following surgical and non-surgical maxillary expansion performed elsewhere.

2. Materials and Methods

Twenty-eight patients requested evaluation following maxillary expansion performed elsewhere during a 30-months period. Complete clinical records with pre- and post-expansion cone beam computed tomography (CBCT) and treatment photographs were collected for analysis.

3. Results

Complete clinical records and CBCT were available in 22 patients. The treatment indication was for OSA in all 22 patients. Six patients underwent distraction osteogenesis maxillary expansion (DOME), five patients were treated by anterior growth guidance appliance (AGGA), two patients were treated by daytime-nighttime appliance (DNA), four patients were treated by advanced lightwire functionals appliance (ALF), and five patients were treated by mini-screw assisted rapid palatal expansion (MARPE).

3.1. Distraction Osteogenesis Maxillary Expansion (DOME)

DOME was described by Liu, *et al.*[16]. It is a modification of the traditional surgically-assisted rapid palatal expansion (SARPE) with several mini-screws added to a tooth-borne expander for improved skeletal anchorage. The use of piezoelectric saw for osteotomies was also advocated. The goal of the modifications was to improve the anchorage and improve skeletal expansion. Six patients with a mean age of 25.2 years (range 26-36 years) underwent DOME. The evaluation found that the expansion pattern was the same as traditional SARPE. The diastema creation was between 10-16 mm in the patients evaluated. The ANS separated in all patients, but PNS separation did not occur in any of the patients. The ratio of diastema: ANS separation was between 2:1 and 3:1.

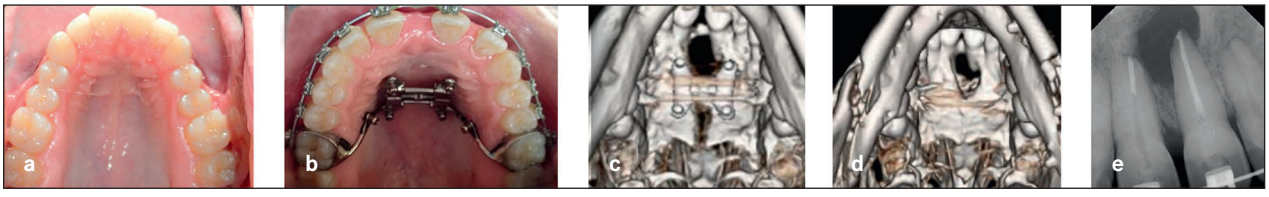

Figure 1

31-year-old man underwent DOME. (a) Preoperative palatal view. (b) Postoperative palatal view after expansion. (c) CBCT axial view showing a large anterior expansion 8 months postoperatively. (d) CBCT axial view showing a large bony defect at anterior maxilla involving the incisor roots two years postoperatively. (e) Periapical dental imaging after apicoectomy and endodontic therapy of maxillary central incisors. The prognosis of the teeth is guarded.

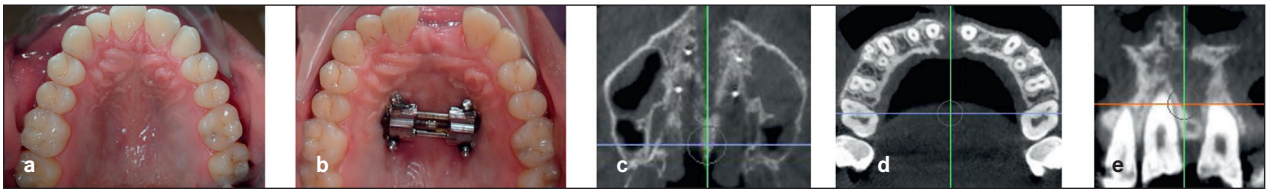

Figure 2

26-year-old man underwent DOME. (a) Preoperative palatal view. (b) Postoperative palatal view after expansion with a 12 mm diastema. (c) CBCT axial view showing large anterior expansion at the completion of the expansion. (d) CBCT axial view showing minimal bone fill two years postoperatively. (e) CBCT coronal view showing a large defect at the distraction site extending to the nasal floor with 3 millimeters of bone at the alveolar crest.

Significant asymmetric expansion was found in four patients with hemimaxilla lateralization on one side only. Large bone defects existed between the central incisors at 18 months or beyond in all six patients despite bone grafting attempts in four patients.

Anterior gingival recession occurred in two patients and four incisor teeth required endodontic therapy with long-term guarded prognosis. None of the patients reported improvement in OSA and three patients proceeded with maxillomandibular advancement (Figs. 1 to 4).

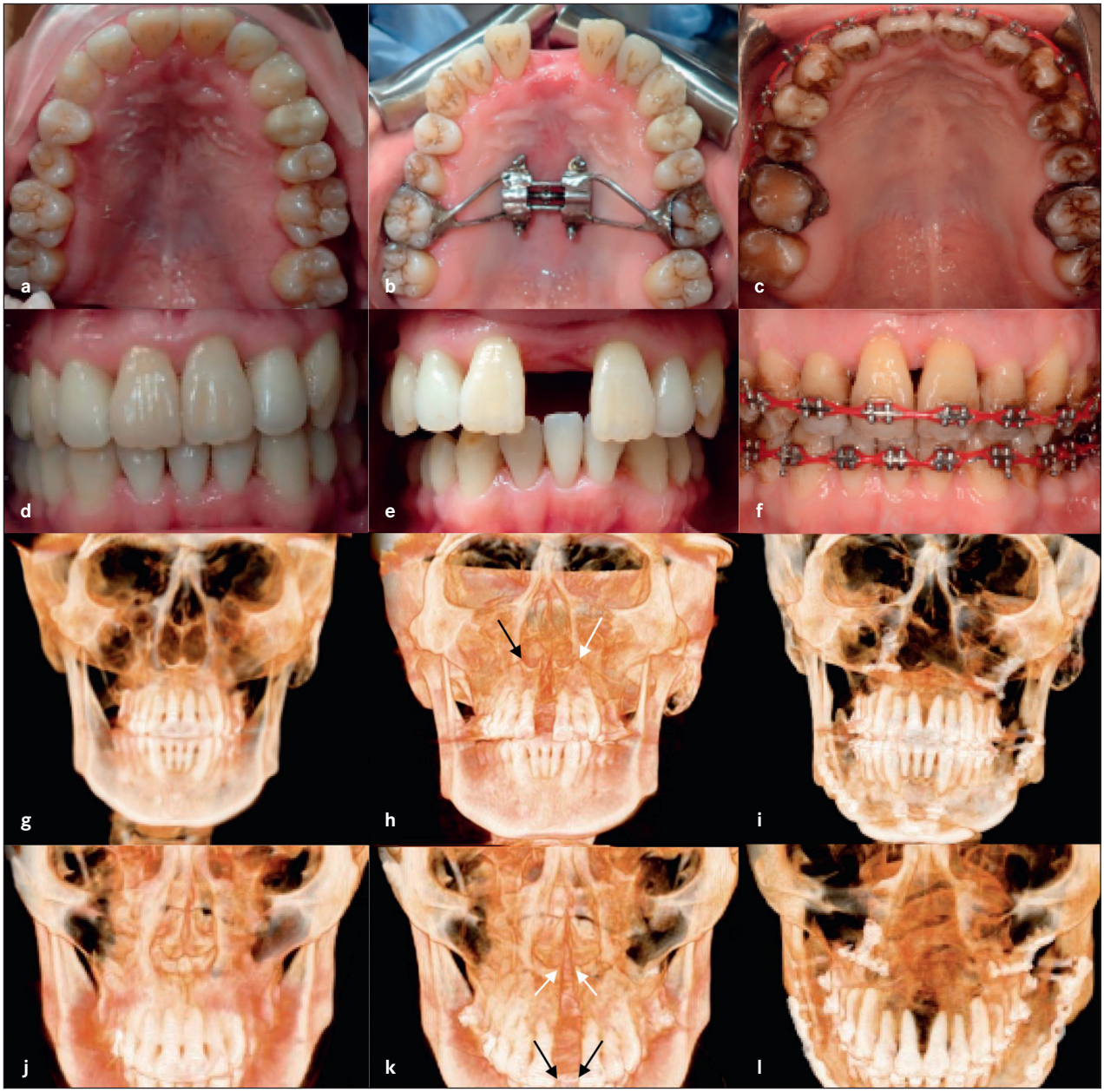

Figure 3

31-year-old man underwent DOME. (a) Preoperative palatal view. (b) Postoperative palatal view after expansion with a 12 mm diastema. (c) Palatal view after diastema closure. (d) Preoperative frontal view. (e) Postoperative frontal view after expansion with a 12 mm diastema. (f) Frontal view after diastema closure. Note the gingival recession and dark triangle at proximal regions. (g) Preoperative CBCT coronal view. (h) Postoperative CBCT coronal view after expansion. Note the significant dentoalveolar displacement contributing to the expansion, the absence of right hemimaxilla movement (black arrow) and slight left hemimaxilla movement (white arrow). (i) Postoperative CBCT after maxillomandibular advancement. (j) Preoperative CBCT showing the nasal floor. (k) Postoperative CBCT after expansion showing the diastema (black arrows) with nasal floor opening (white arrows) from ANS to the premolar region only. (l) Postoperative CBCT after maxillomandibular advancement two years following DOME. Note the bone deficiency between the roots of the maxillary central incisors.

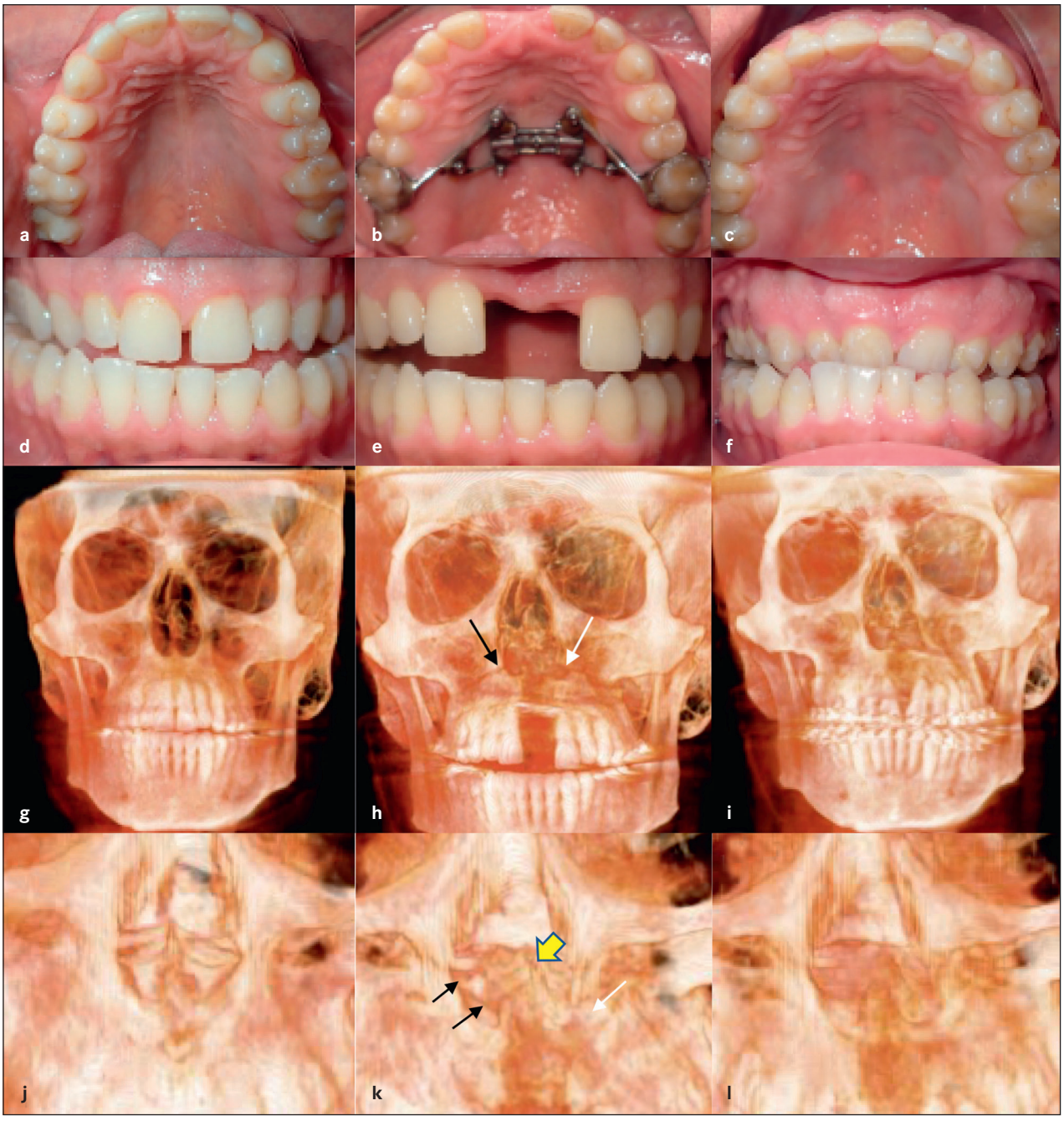

Figure 4

36-year-old man underwent DOME. (a) Preoperative palatal view. (b) Postoperative palatal view after expansion with a 16 mm diastema. (c) Palatal view after diastema closure. (d) Preoperative frontal view. (e) Postoperative frontal view after expansion with a 16 mm diastema. (f) Frontal view after diastema closure. (g) Preoperative CBCT coronal view. (h) Postoperative CBCT coronal view after expansion. Note the significant dentoalveolar displacement contributing to the expansion, the absence of right hemimaxilla movement (black arrow) and the left hemimaxilla movement (white arrow) contributing to asymmetry. (i) Postoperative CBCT after diastema closure. Note the maxillary asymmetry. (j) Preoperative CBCT showing the nasal floor. (k) Postoperative CBCT after expansion showing the intact midpalatal suture (yellow arrow), separation at the right nasal floor with protruding microscrews (black arrow) and the lateralized left hemimaxilla (white arrow). (l) Postoperative CBCT after diastema closure.

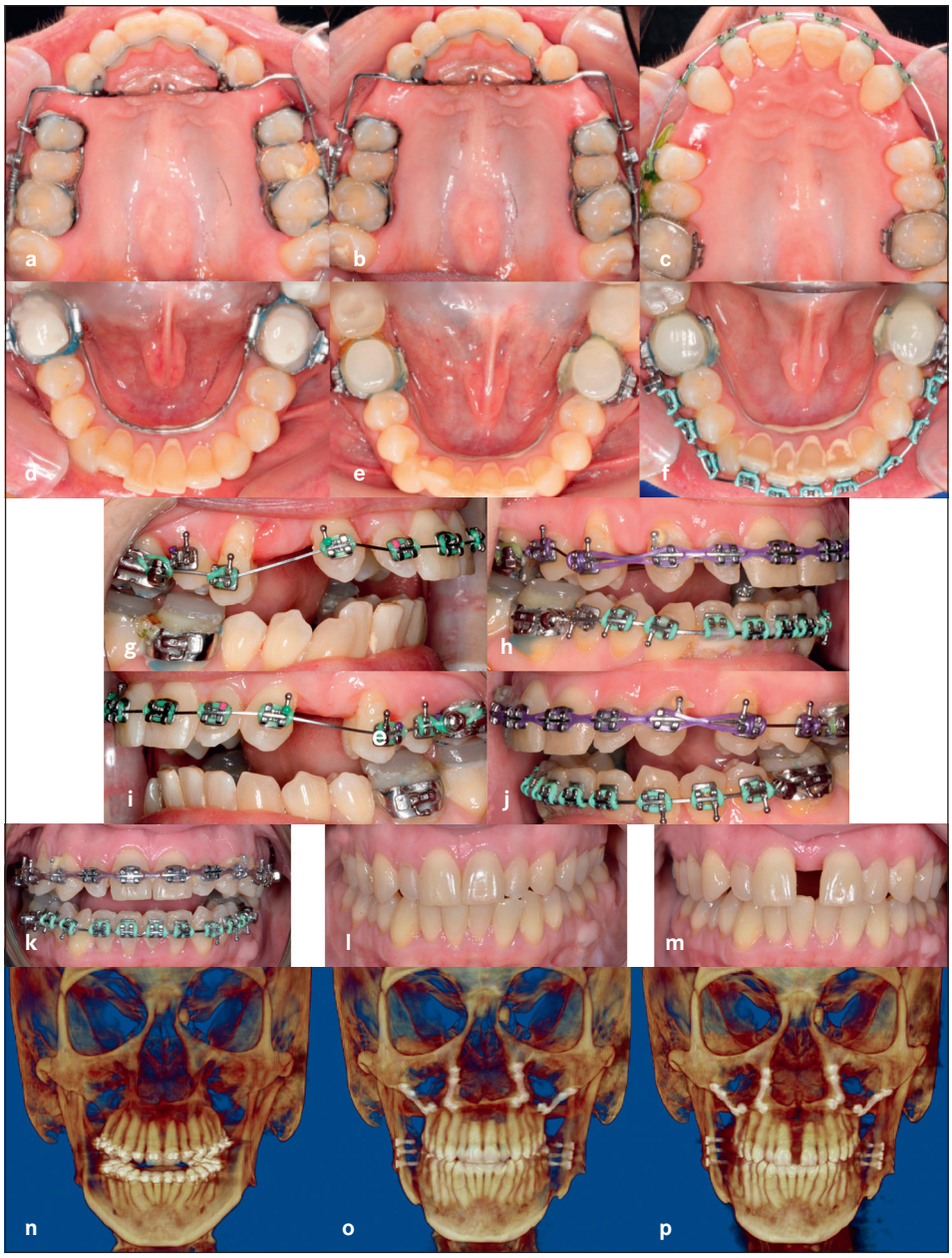

Figure 5

49-year-old woman underwent AGGA. (a) Palatal view during AGGA treatment. (b) Palatal view prior to appliance removal. (c) Palatal view during orthodontic closure of the edentulous space. (d) Mandibular occlusal view during AGGA treatment. (e) Mandibular occlusal view prior to appliance removal. (f) Mandibular occlusal view during orthodontic closure of the edentulous space. (g) Right lateral view in the beginning of the orthodontic closure of the edentulous space. (h) Right lateral view showing closure of the edentulous space. (i) Left lateral view in the beginning of the orthodontic closure of the edentulous space. (j) Left lateral view showing closure of the edentulous space. (k) Frontal view near the completion of the AGGA treatment. Note the lateral displacement of the dentoalveolus. (l) Frontal view after removal of the orthodontic appliance and following maxillomandibular advancement. Note the normalization of the dentoalveolus. (m) Frontal view after nasomaxillary expansion by endoscopically assisted surgical expansion (EASE). Note the absence of dentoalveolar displacement. (n) Postero-anterior (PA) skull view at the completion of the AGGA treatment. Note the lateral displacement of the dentoalveolus. (o) PA skull view with removal of the orthodontic appliance and following maxillomandibular advancement. Note the normalization of the dentoalveolus. (p) PA skull view post nasomaxillary expansion by EASE. Note the nasomaxillary widening without dentoalveolar displacement.

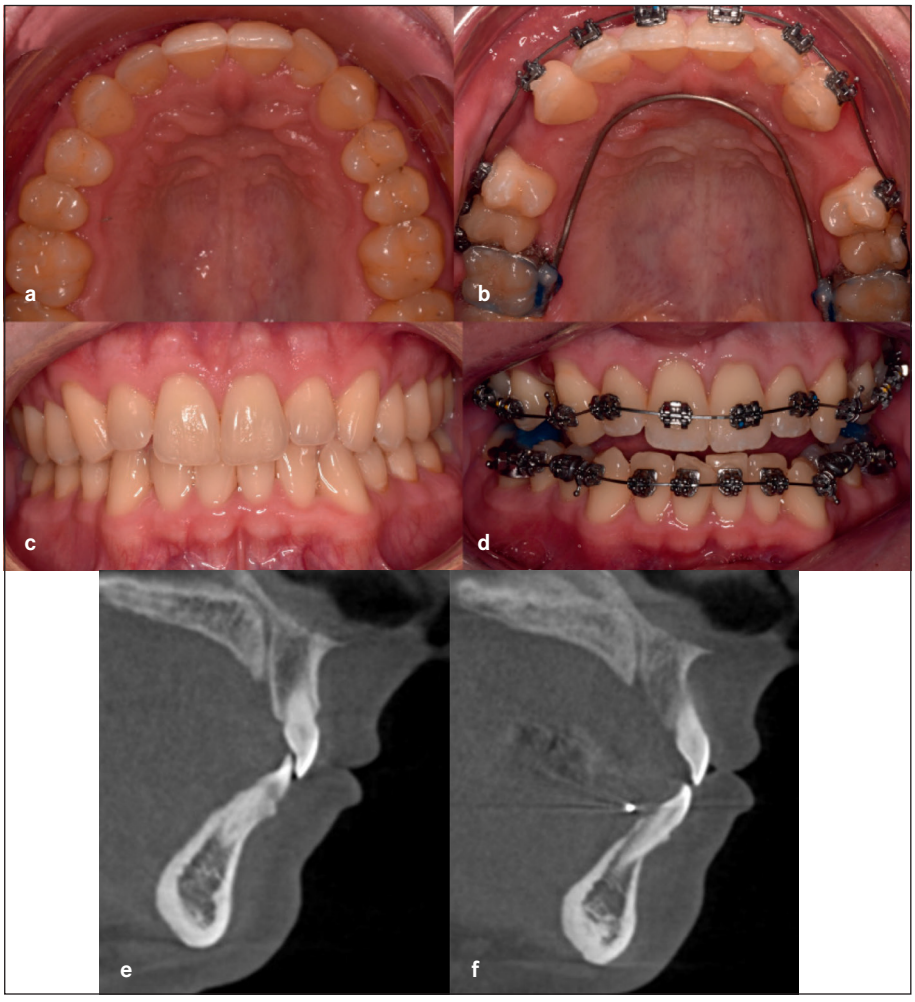

Figure 6

28-year-old man underwent AGGA treatment. (a) Pretreatment maxillary occlusal view. (b) Maxillary occlusal view after AGGA expansion. (c) Pretreatment frontal view. (d) Frontal view after AGGA expansion. (e) CBCT sagittal view showing the alveolar bone at central incisor. (f) CBCT sagittal view showing the reduction of the central incisor labial bone.

3.2. Anterior Growth Guidance Appliance (AGGA)

AGGA has been advocated to promote facial growth due to the physiologic stimulation by the appliance[8,9]. Although the treatment indication was for OSA, no peer-review studies are currently available on the impact of this treatment in OSA. Five patients with a mean age of 32.6 years (range 28-49 years) that underwent AGGA reported no improvement in their symptoms. All five patients reported significant teeth mobility. The CBCT showed dental and dentoalveolar displacement in the maxillary dentition. Thinning and destruction of the labial/buccal alveolar bone with horizontal and vertical bone loss occurred in the anterior dentition in all five patients, and the midpalatal suture remained fused in all of the patients (Figs. 5 to 7).

3.3. Daytime-Nighttime Appliance (DNA)

The DNA appliance has been advocated for the treatment of OSA. Although scant case reports with the use of DNA can be found, no peer-reviewed scientific evidence concerning the role of these devices in the treatment of OSA is currently available[23,24]. The two patients that underwent DNA treatment reported no improvement in their OSA symptoms. The clinical records and CBCT showed the maxillary expansion were purely dental and dentoalveolar in nature without separation of the midpalatal suture (Fig. 8).

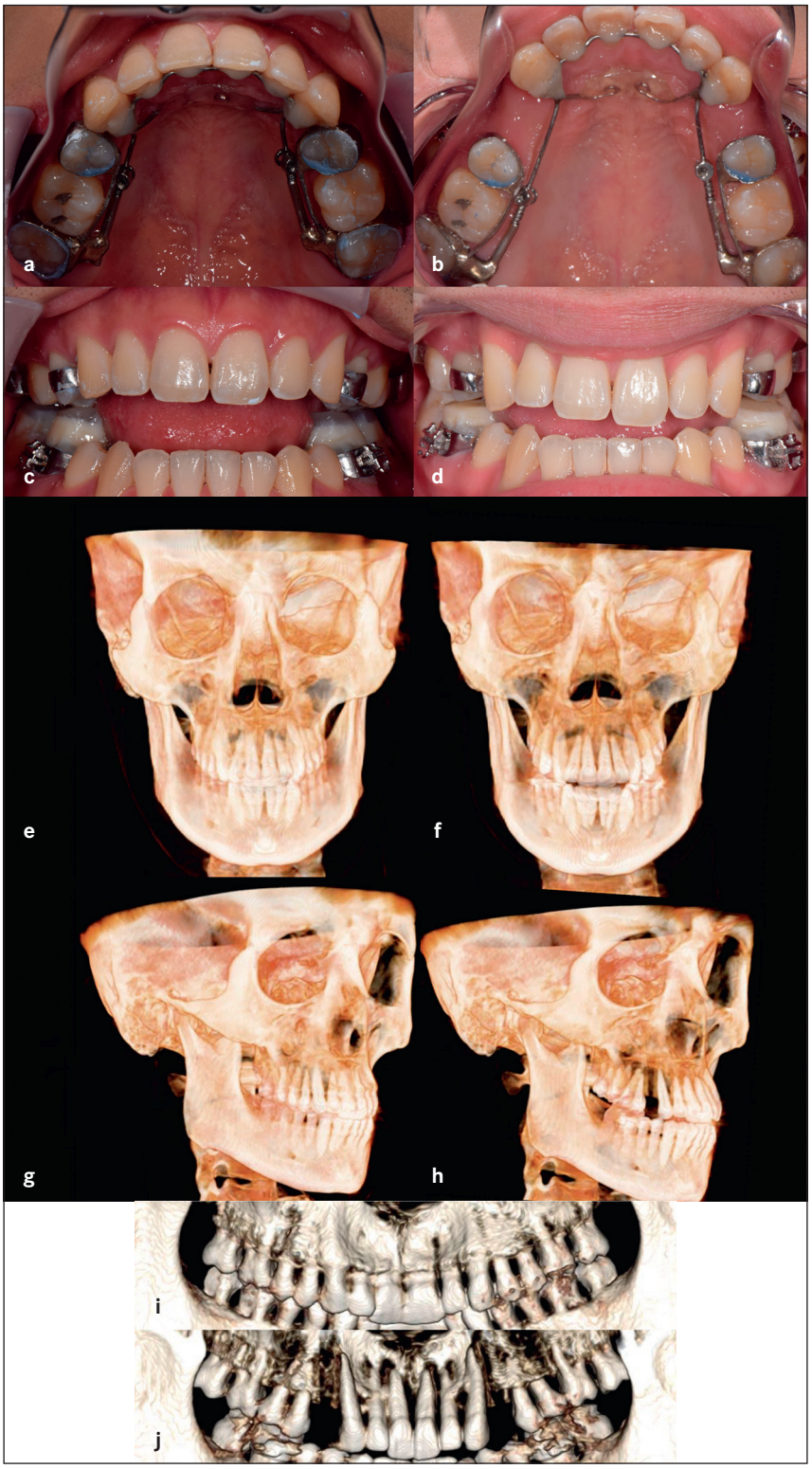

Figure 7

21-year-old man underwent AGGA treatment. (a) Palatal view with AGGA appliance. (b) Palatal view at the completion of the AGGA activation. Note the edentulous space and the significant proclination of the dentition. (c) Frontal view before AGGA activation. (d) Frontal view at the completion of the AGGA activation. (e) Postero-anterior (PA) skull view pretreatment. (f) PA skull view post AGGA activation. (g) ¾ skull view pretreatment. (h) ¾ skull view post AGGA activation. (i) CBCT view pretreatment. (j) CBCT view post AGGA treatment. Note the alveolar bone destruction and recession.

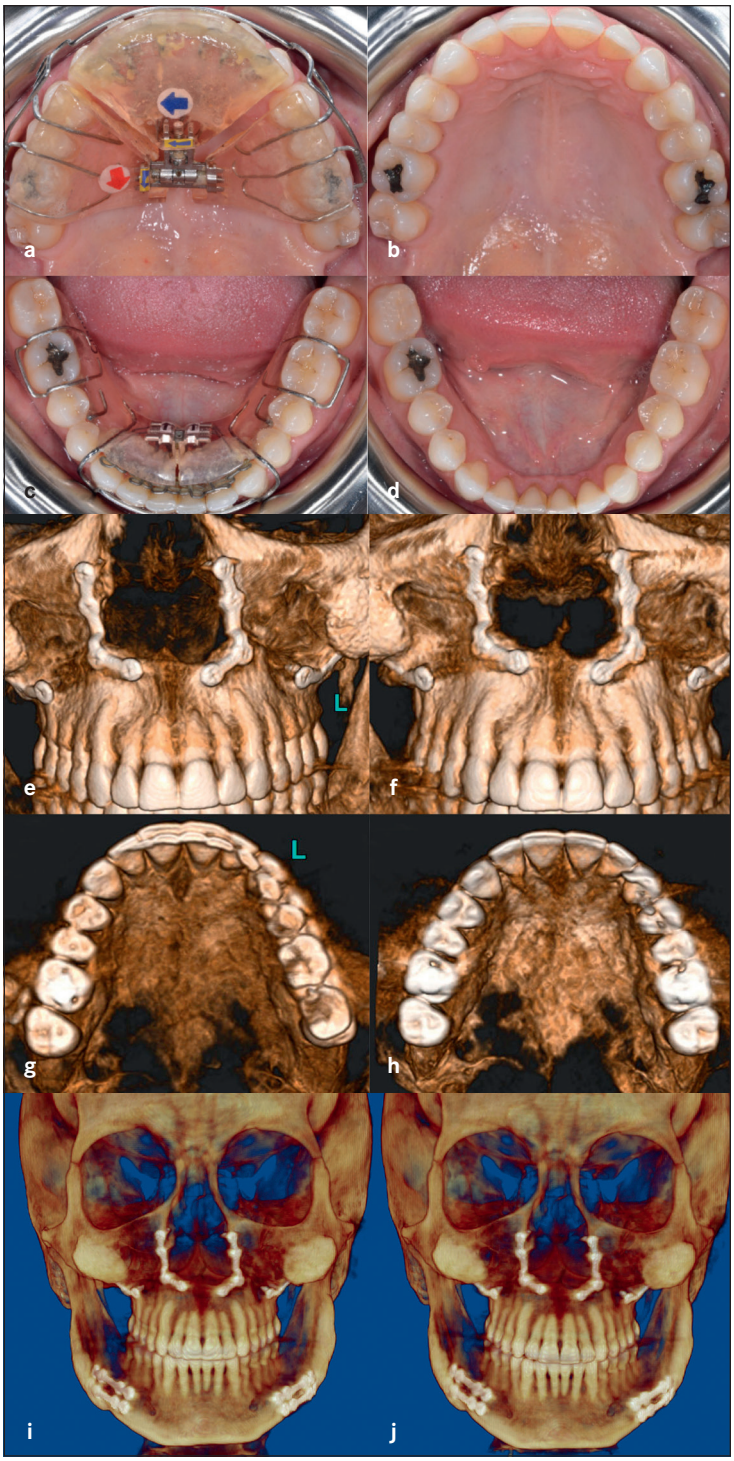

Figure 8

60-year-old woman with prior maxillomandibular advancement underwent DNA treatment. (a) Maxillary occlusal view with DNA appliance. (b) Maxillary occlusal view at completion of expansion. (c) Mandibular occlusal view with DNA appliance. (d) Mandibular occlusal view at completion of expansion. (e) Pretreatment CBCT frontal view. (f) Posttreatment CBCT frontal view. Note the lateralization of the alveolus without midpalatal suture separation. (g) Pretreatment CBCT maxillary occlusal view. (h) Posttreatment CBCT maxillary occlusal view. Note the intact midpalatal suture. (i) Pretreatment PA skull view. (j) Posttreatment PA skull view. Note the intact midpalatal suture with lateralization of the dentoalveolus.

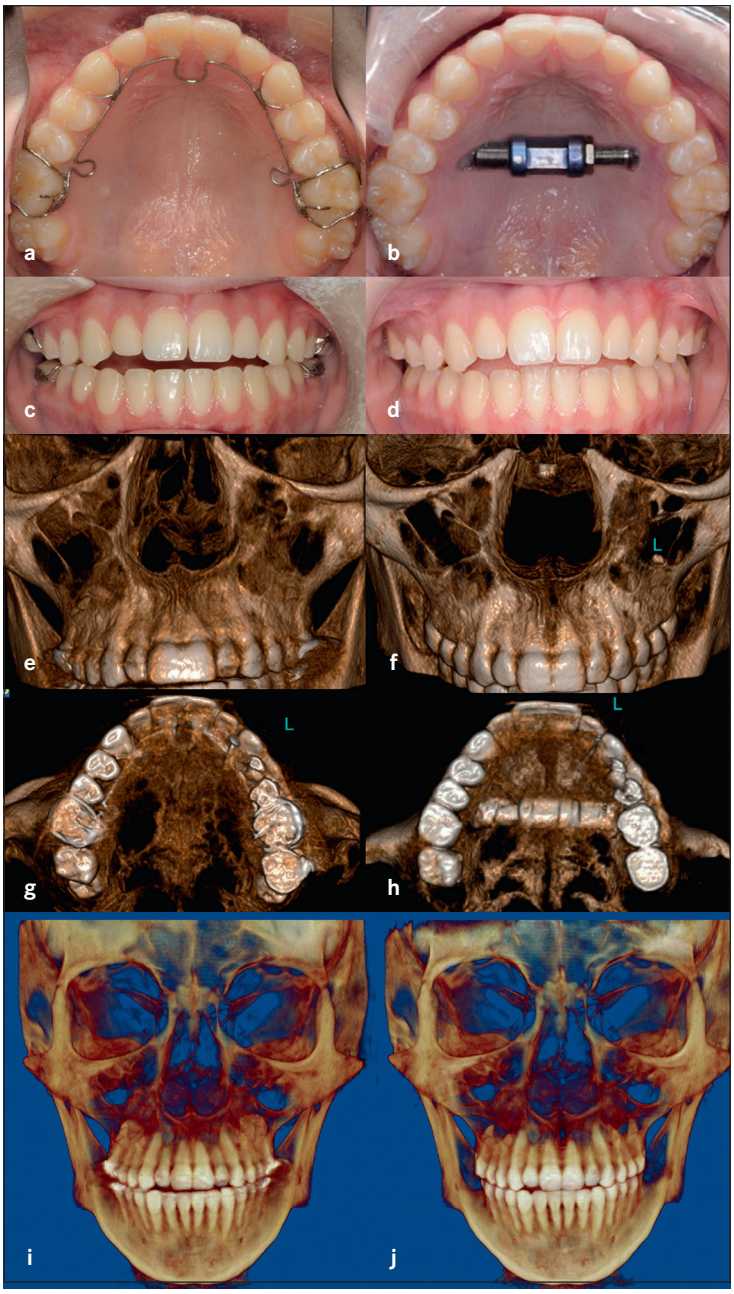

Figure 9

14-year-old girl underwent ALF treatment. (a) Palatal view with ALF appliance. (b) Palatal view posttreatment with transpalatal distraction (TPD) after removal of the ALF appliance. (c) Frontal view posttreatment with ALF appliance. (d) Frontal view posttreatment with TPD after removal of ALF appliance. (e) Posttreatment ALF CBCT frontal view. Note the intact midpalatal suture. (f) Posttreatment TPD CBCT frontal view. Note the nasal airway expansion with midpalatal suture separation. (g) Palatal view posttreatment with ALF. Note the intact midpalatal suture. (h) Palatal view posttreatment with TPD. Note the separation of the midpalatal suture. (i) PA skull view posttreatment with ALF. Note the intact midpalatal suture and lateralized dentoalveolus. (j) PA skull view posttreatment with TPD after removal of ALF appliance. Note the nasomaxillary expansion, midpalatal suture separation and normalization of the dentoalveolus.

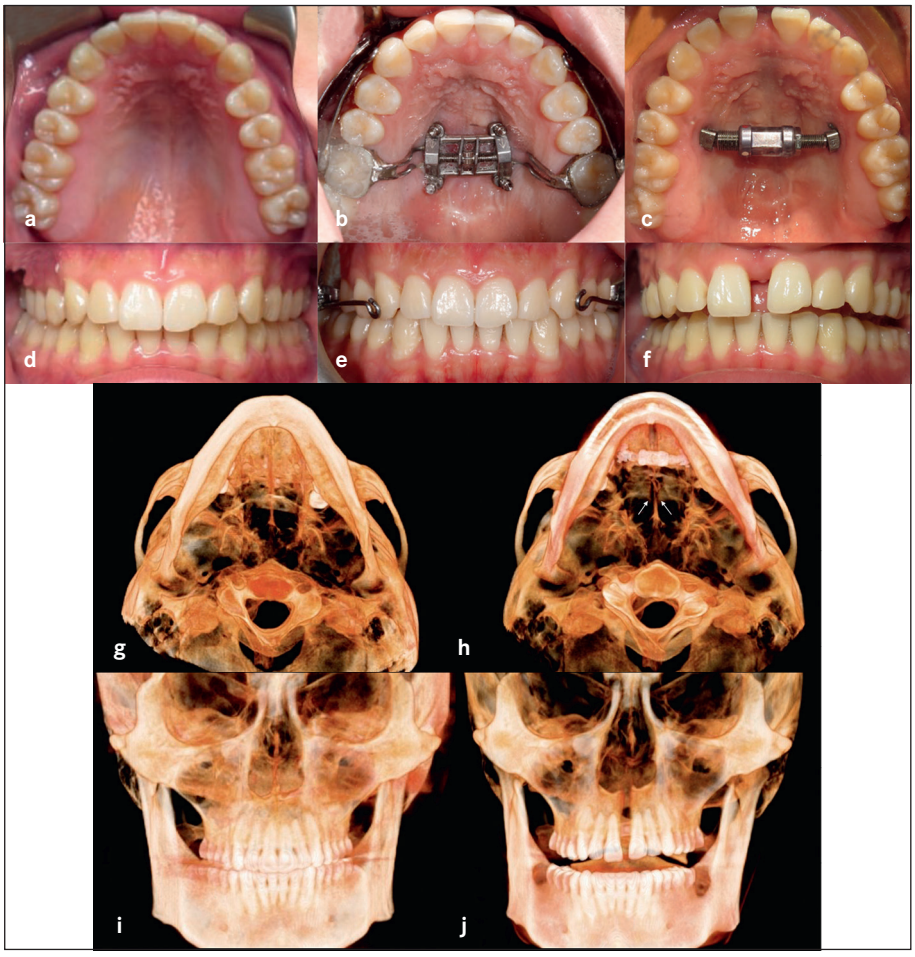

Figure 10

20-year-old man underwent MARPE treatment. (a) Pretreatment palatal view. (b) Posttreatment with MARPE without separation of the midpalatal suture. (c) Posttreatment with EASE after MARPE appliance removal. (d) Pretreatment frontal view. (e) Posttreatment with MARPE without separation of the midpalatal suture and the absence of diastema. (f) Posttreatment with EASE after MARPE appliance removal. Note the skeletal expansion without lateralization of the dentoalveolus. (g) CBCT palatal view after MARPE appliance removal. Note the intact midpalatal suture. (h) CBCT palatal view after EASE. Note the parallel midpalatal separation and opening of the posterior nasal spine (white arrows). (i) CBCT frontal view after MARPE appliance removal. (j) CBCT frontal view after EASE.

3.4. Advanced Lightwire Functionals Appliance (ALF)

OSA was the treatment indication for the four patients that underwent ALF therapy. The mean age was 22 years (range 14-21 years). Although ALF has been advocated in orthodontics by some practitioners[6,25], there is currently no objective evidence that ALF treatment improves OSA and, indeed, no peer-reviewed scientific evidence concerning the role of these devices in the treatment of OSA is currently available. All four patients reported no improvement of nasal breathing or OSA symptoms following ALF treatment. Lateralization of the dentoalveolus was evident in the clinical photos and CBCT in all the patients and the midpalatal suture did not separate in any of the patients (Fig. 9).

3.5. Mini-screw Assisted Rapid Palatal Expansion (MARPE)

MARPE has been advocated in recent years to achieve a greater skeletal expansion with improved skeletal anchorage and reduction of undesirable dental impact[4,11,27]. A review of MARPE in 264 patients showed an average age of 12.3 years[15]. Therefore, this approach may have limitations beyond adolescents and young adults.

All five patients that underwent MARPE expansion failed to achieve midpalatal suture separation, and the mean age was 26.2 years (range 20-36 years). Although some dental/dentoalveolar tilting occurred, it was less than the other dental expansion methods described in this report (Fig. 10). The palatal screws showed tilting/angulation or "cheese-wiring" through the nasal floor with limited lateralization of the dentition in all patients. No improvement of symptoms was reported.

4. Discussion

Nasal obstruction leads to compensatory oral breathing, resulting in increased airway resistance during sleep[7,26]. Oral breathing with mouth opening contributes to tongue retrodisplacement, upper airway collapse, and altered airway muscle activity[1,2,12,19,28]. Multiple investigators have shown that OSA can be induced in healthy volunteers when the nose is artificially obstructed by nasal packing[7,20,22,26,30]. Nasal surgery has been demonstrated to reduce nasal resistance and improve OSA[3,18]. Indeed, the nose is an important element in the development and treatment of OSA. Evidence suggests that maxillary expansion widens the mid-palatal suture and enlarges the nasal airway resulting in the reduction of nasal resistance[10,13,14,29]. This effect renders a less collapsible airway to negative intraluminal pressure, leading to OSA improvement[14]. Therefore, maxillary expansion must target the separation of the midpalatal suture, resulting in nasal sidewall lateralization to achieve nasal airway expansion.

It is well-known that separation of the midpalatal suture becomes increasingly more difficult with age due to ossification and maturation of the skeleton[17,21]. Therefore, the dental tipping, thinning, and destruction of the labial/buccal alveolar bone, gingival recession, and failure of midpalatal suture separation found in these adult patients that underwent non-surgical expansion were not surprising but expected. Unfortunately, the dental health and alveolar support were permanently compromised in some patients following their treatment, while OSA was not improved.

The addition of mini-screws to improve skeletal anchorage in minimizing unfavorable dental changes clearly makes physiologic sense. However, MARPE was unsuccessful in achieving skeletal expansion. Therefore, limitations exist in applying this approach to all patients, even in young adults. The limitation can be overcome when maxillary sutures were strategically separated along with the application of a skeletal distractor, despite prior failure of MARPE expansion (Fig. 10).

It should be emphasized that although surgically assisted maxillary expansion can achieve skeletal expansion with midpalatal suture separation, the expansion pattern can vary, as seen in the DOME patients. Additionally, the extent of dental expansion was much greater than the skeletal expansion, along with significant bone loss and dental devitalization. This is possibly related to the excessive expansion performed in an attempt to maximize the nasal expansion, thus resulting in complications. The asymmetric expansion and the lack of hemimaxilla lateralization are likely related to the slanted Le Fort I osteotomy performed in these patients, as all of the patients were noted to have non-horizontal but angulated Le Fort I osteotomy pattern.

5. Conclusion

The application of maxillary expansion has evolved from improving dental crossbites to improving breathing and sleep. This is a new and exciting arena for the dental profession. However, many maxillary expansion methods that are currently being used have minimal outcomes data. This deficiency is increasingly being recognized. A rigorous scientific approach and critical analyses of these methods are needed to determine their impact and whether the desired outcomes can be achieved.

Links of interest

The authors declare that they have no interest in the data published in this article.

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Original article

Persistent pediatric obstructive sleep apnea treated with skeletally anchored transpalatal distraction

Kasey LI[1*], Tomonori IWASAKI[2], Stacey QUO[3], Connor LI[1], Kara YOUNG[1], Eileen LEARY[4], Christian GUILLEMINAULT[5]

[1] Sleep Apnea Surgery Center, 1900 University Avenue, Suite 105, East Palo Alto, CA, USA
[2] Developmental Medicine, Health Research Course, Graduate School of Medical and Dental Sciences, Kagoshima University, 8-35-1 Sakuragaoka, Kagoshima 890-8544, Japan
[3] School of Dentistry, University of California San Francisco, 707 Parnassus Ave, San Francisco, CA 94143, USA
[4] Center for Sleep Sciences and Medicine, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA
[5] Deceased. Sleep Medicine Division, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA

KEYWORDS:
OSA / TPD / RPE / EASE / RME / MARPE / Sleep apnea / Maxillary expansion / Nasomaxillary expansion

ABSTRACT – Introduction: *The aim of this study was to evaluate the impact of nasomaxillary expansion using skeletally anchored transpalatal distraction (TPD) in children without transverse maxillary deficiency that were previously treated by rapid palatal expansion (RPE).* **Materials and Methods:** *Twenty-nine consecutive children were treated by TPD. Twenty-five children, aged 10-16 years completed pre- and post-operative clinical evaluations, questionnaires (OSA-18), cone beam computed tomography (CBCT), and polysomnography (PSG). The pre- and post-operative CBCT data were used to reconstruct the 3-dimensional shape of the upper airway. Two measures of airflow function (pressure and velocity) were simulated by using computational fluid dynamics (CFD) at four different airway segments (nasal, nasopharyngeal, oropharyngeal and hypopharyngeal).* **Results:** *Twenty-three patients (92%) experienced improvement based on PSG. The apnea hypopnea index (AHI) improved from 6.72±4.34 to 3.59±5.11 (p<0.001) events per hour. Clinical symptoms based on OSA-18 scores were improved in all patients. Twenty-five patients (100%) had successful expansion defined as separation of the midpalatal suture at least 1 mm from anterior nasal spine (ANS) to posterior nasal spine (PNS). The nasal sidewall widening was 2.59±1.54 mm at canine, 2.91±1.23 mm at first molar and 2.30±1.29 mm at PNS. The ratio of dental expansion to nasal expansion was 1.12:1 (2.90 mm:2.59 mm) at canine and 1.37:1 (3.98 mm:2.91 mm) at first molar. The nasal airflow pressure reduced by 76% (-275.73 to -67.28 Pa) and the nasal airflow velocity reduced by over 50% (18.60 to 8.56 m/s).* **Conclusions:** *Nasomaxillary expansion by skeletally anchored TPD improves OSA in children without transverse maxillary deficiency that were previously treated by RPE. A nearly parallel anterior-posterior opening of the mid-palatal suture achieves enlargement of the entire nasal passage with improvement of the airflow characteristics in the nasal and pharyngeal airway. The improved airflow characteristic is significantly correlated with the improved polysomnographic findings, thus demonstrating that nasomaxillary expansion in previously expanded patients is a viable treatment option.*

* Correspondance : drli@sleepapneasurgery.com

1. Introduction

Rapid palatal expansion (RPE) is a widely performed orthodontic procedure to treat unilateral or bilateral crossbites due to maxillary constriction. RPE separates the mid-palatal suture and pushes the maxilla's two halves apart, resulting in a wider maxilla and lateral nasal wall, yielding nasomaxillary expansion[35]. It was adapted as a treatment of obstructive sleep apnea (OSA) in children with narrow hard palates (transverse maxillary deficiency) with numerous studies reporting improvement of OSA using RPE as a primary or secondary treatment[6,31,32,36]. A review of 17 maxillary expansion studies found consistent improvement in the apnea hypopnea index (AHI) and lowest oxygen saturation, but with residual OSA after expansion[4].

One major limitation utilizing RPE in treating OSA is the change in occlusion. Expansion in the absence of a skeletal or dental crossbite results in an excessively wide maxilla and uncoordinated dental arches, and in these cases bimaxillary expansion has been utilized with some improvement[32]. However, expansion is discontinued when the maxilla is no longer narrowed, or when dental crowding or the crossbite is corrected, thus limiting the nasal airway expansion. Moreover, the widening of the lateral nasal wall is less than the maxillary widening as there is some lateral displacement of the alveolus from teeth tipping buccally rather than sole separation of the mid-palatal suture[11,12]. Indeed, it has been shown that most of the maxillary widening in RPE is dentoalveolar changes instead of skeletal widening[5,13,20,38], and the pattern of mid-palatal suture opening is inconsistent[25].

Skeletally anchored palatal expansion with miniscrews has been advocated to improve the skeletal effect and reduce the undesirable dental impact in RPE[3,16,34]. This approach is usually advocated in late adolescent or young adult patients when surgery is likely necessary to facilitate successful expansion. Limited case studies report improvement in OSA in young adults[3,16].

Since the early 2000s, we evaluated children with persistent or recurrent OSA previously treated by RPE and adenotonsillectomy[14,15]. Due to the scarcity of treatment options, we attempted further expansion of the maxilla in an effort to gain more space in the nasal cavity to reduce nasal resistance. A skeletally anchored transpalatal distractor (TPD)[28] was used in order to maximize nasal airway expansion while minimizing the dentoalveolar widening in an already expanded maxilla. This study aimed to evaluate the outcome of nasomaxillary expansion using TPD based on polysomnographic data and clinical symptoms. Skeletal, dental and airway changes based on cone beam computed tomography (CBCT) and computational fluid dynamics (CFD) were also analyzed.

2. Materials and Methods

2.1. Subjects

This retrospective study was approved by Institutional Review Board (#15494). Informed consent was obtained from the parents for transpalatal distraction (TPD) treatment as well as discussion for the need for orthodontic treatment post-expansion. Twenty-nine consecutive children (ages 10-16) with persistent OSA who were previously treated by RPE underwent TPD to expand the nasomaxillary complex. All children had the absence of narrow hard palates (transverse maxillary deficiency) or crossbite, had prior adenotonsillectomy or had small tonsil size (grade 1 and 2) where adenotonsillectomy was not warranted. Data evaluated included: clinical records, polysomnography (PSG) records, OSA-18 questionnaire by the caretaker, cone beam computed tomography (CBCT), and computational fluid dynamics (CFD) results.

2.2. Surgical Procedure: transpalatal distraction

The same surgical procedure was applied to all patients and performed by the same surgeon. Due to the extended head position necessary for device placement as well as the decision to take extra precaution in managing pediatric patients during the operation, the procedure was performed under either general anesthesia or intravenous sedation. The distractor (TPD, KLS Martin Group, Jacksonville, FL) was inserted onto the palate at the second premolar/first molar region. Incisions were made at the proposed footplate sites for the TPD. Limited subperiosteal dissection was performed to create a pocket that allowed the footplate to be inserted. A single screw was used to stabilize each footplate, and the TPD was expanded so the footplates fully engaged the palatal bone. All patients were discharged the same day.

2.3. Expansion process

TPD was activated between 3-5 days following surgery at 0.1-0.3 mm per day. The expansion process was deemed completed either when the patient experienced no further clinical improvement with continual expansion, or when the occlusion was altered so that further alteration would result in orthodontic difficulties. The TPD was locked at the completion of the expansion and removed under local anesthesia three months later.

2.4. Polysomnography (PSG)

PSG was performed usually within one year before surgery, and postoperative PSG was performed at most 12 weeks after the TPD was removed. The in-lab study included electroencephalogram, eye movements, chin electromyogram, leg electromyogram. The respiration was monitored with a nasal cannula, a mouth thermistor, thoracic and abdominal uncalibrated inductive plethysmograph bands, a snore microphone, a position sensor and a finger pulse oximeter. PSG scoring was based on the 2012 American Academy of Sleep Medicine (AASM) recommendations[2].

2.5. Questionnaires

OSA-18 questionnaire is a subjective questionnaire of 18 items to evaluate the quality of life (QOL). The questions were divided into six domains: sleep disturbance, physical suffering, emotional distress, daytime problems, care-giver concerns, and total quality of life. OSA-18 is a valid, reliable, and sufficiently discriminative to measure QOL in children with OSA[10]. The questionnaire was administered at the preoperative appointment (1-3 weeks prior to surgery) and between 3-4 months postoperatively just before TPD removal.

2.6. Cone Beam Computed Tomography (CBCT)

The use of CBCT is now widely utilized in routine orthodontic practice and is gradually replacing pre- and post-treatment plane radiograph including panoramic and cephalometric radiographs for documentation purposes. Additionally, CBCT has been utilized to assess treatment outcomes in maxillary expansion in the pediatric population[18,19]. Therefore, all patients underwent CBCT preoperatively and within six weeks postoperatively. CBCT scans were acquired in the supine position in extended field modus (FOV: 16 x 22 cm, scanning time 2 x 20 s, voxel size 0.4 mm, NewTom 3D VGI, Cefla North America, Charlotte, NC). Data from CBCT were exported in Digital Imaging and Communications in Medicine (DICOM) format. Data from CBCT were exported in Digital Imaging and Communications in Medicine (DICOM) format into InVivo5© software (Anatomage, San Jose, CA, USA) and were reoriented with the palatal plane parallel to the floor in the sagittal and coronal planes. The following measurements were recorded by dental radiology technicians blinded to the study: intercanine width, lateral nasal wall width at canine, intermolar width, nasal sidewall width at first molar, lateral nasal wall width at posterior nasal spine (Fig. 1).

2.7. Simulation of Airway Ventilation Conditions with Computational Fluid Dynamics (CFD)

Volume-rendering software (INTAGE Volume Editor, CYBERNET, Tokyo, Japan) was used to generate 3D volume data for the upper airway. Using mesh-morphing software (DEP Mesh Works/Morpher, IDAJ, Kobe, Japan), the 3D models were subsequently converted to a smoothed model without losing the patient-specific airway shape. CFD was used to simulate ventilation of the upper airway models (Fig. 2)[18,19]. The models were exported to fluid dynamics software (PHOENICS, CHAM-Japan, Tokyo, Japan) in stereolithographic format, and the fluid was assumed to be Newtonian, homogeneous, and incompressible. Elliptic-staggered equations and a continuity equation were used in the analysis. The CFD of the upper airway models was analyzed under the following conditions: volumetric flow rate of 7 ml/s/kg no-slip condition at the wall surface, and 300 iterations to calculate mean values. Convergence was judged by monitoring the magnitude of the absolute residual sources of mass and momentum, normalized to their respective inlet fluxes. The iteration was continued until all residuals fell below 0.2%. Simulation of estimated airflow pressure and velocity was performed at the nasal airway, nasopharyngeal airway (NA), oropharyngeal airway (OA), and hypopharyngeal airway (HA).

2.8. Statistical Analysis

Descriptive statistics and frequency distributions were performed on all demographic and clinical characteristics. Summary measures were calculated as means, and standard deviation for continuous

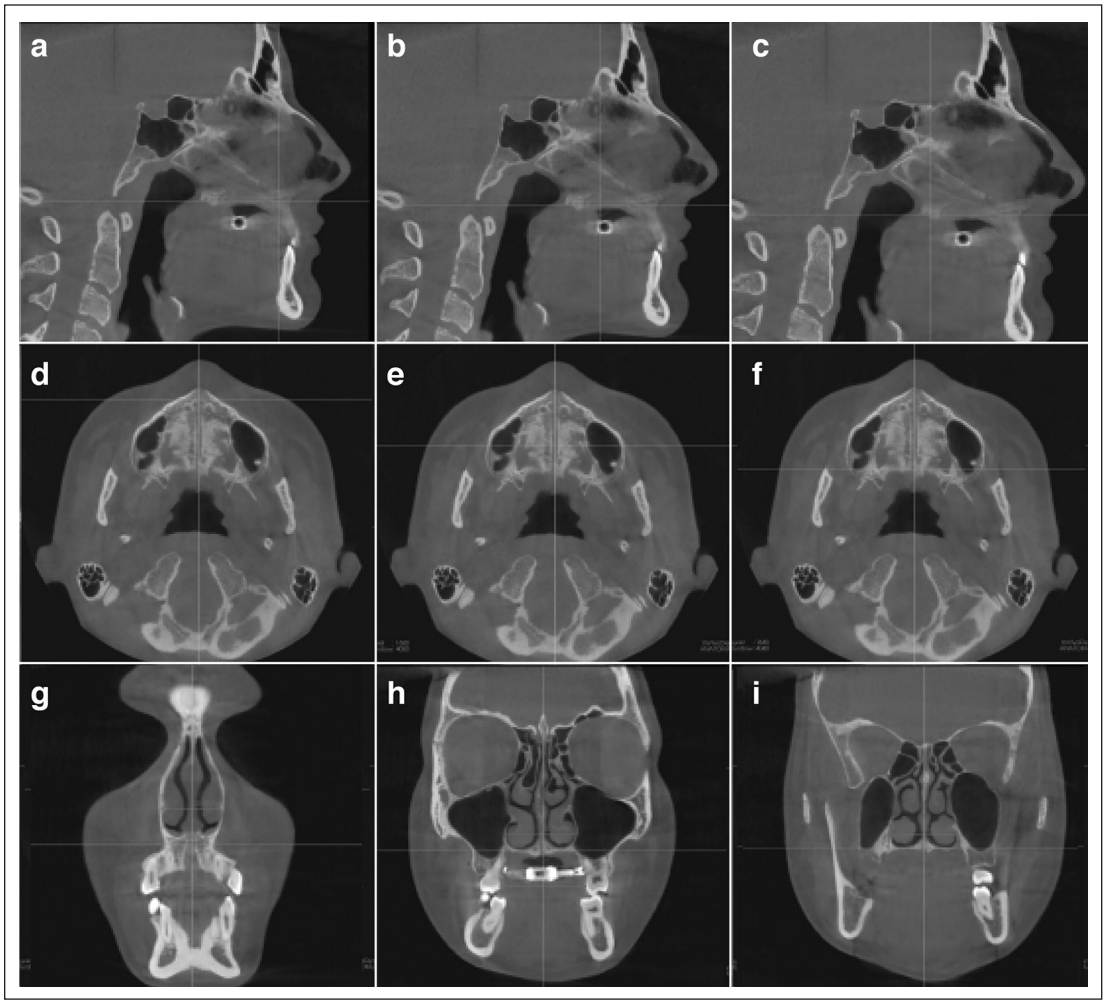

Figure 1

CBCT measurements. (a) Sagittal view at the location of anterior measurement at canine. (b) Sagittal view at the location of measurement at first molar. (c) Sagittal view at the location of posterior measurement at PNS. (d) Axial view at the location of the anterior measurement at canine. (e) Axial view at the location of measurement at the first molar. (f) Axial view at the location of the posterior measurement at posterior nasal spine (PNS). (g) Frontal view of intercanine width and nasal sidewall width measurement. (h) Frontal view of intermolar width and nasal sidewall width measurement. (i) Frontal view of nasal sidewall width measurement at PNS.

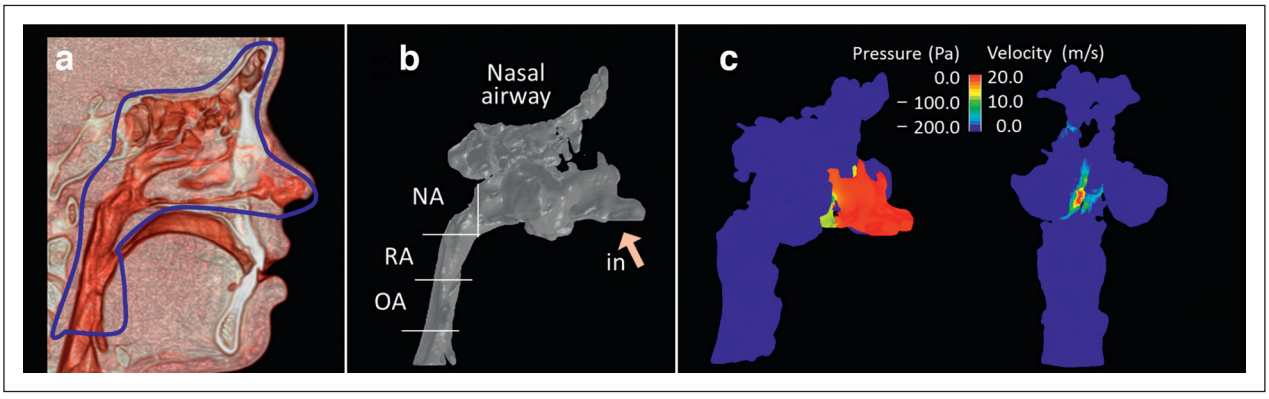

Figure 2

Evaluation of upper airway ventilation using computed fluid dynamics. (a) Extraction of the upper airway. (b) Construction of three-dimensional upper airway model and numeric simulation (inspiration air mass flow: 7 ml/s/kg), at nasopharynx (NA), oropharynx (RA), hypopharynx (OA). (c) Evaluation of the upper airway pressure (left) and velocity (right).

variables or counts and proportions for categorical variables were also calculated. Paired sample Wilcoxon signed-rank test was used to compare preoperative and postoperative parameters due to the small sample size and skewed distribution of some measures. The data was evaluated for extreme or implausible values and a 2-sided P value less than 0.05 was used to indicate statistical significance. All analyses were performed using R Studio version 1.1.383.

Table 1. Respiratory data, symptoms, pressure and velocity changes before and after transpalatal distraction (TPD).

n = 25	Preoperative	Postoperative	Treatment change	p-value*
	Mean ± DS	Mean ± DS	Mean ± DS	
AGE	13.16 ± 1.46			
BMI	17.51 ± 3.38	17.56 ± 3.38		**0.44**
AHI	6.72 ± 4.34	3.59 ± 5.11		**< 0.001**
OSat	92.72 ± 2.21	93.89 ± 1.20		**< 0.001**
Sleep disturbance	10.12 ± 3.17	5.48 ± 0.92		**< 0.001**
Physical suffering	10.12 ± 4.02	6.40 ± 2.12		**< 0.001**
Emotional Distress	9.36 ± 3.41	6.32 ± 2.42		**< 0.001**
Daytime Problems	13.56 ± 3.57	7.16 ± 2.03		**< 0.001**
Caregiver Concerns	12.80 ± 4.93	8.04 ± 2.88		**< 0.001**
QOL (0-10)	5.32 ± 0.90	7.64 ± 0.76		**< 0.001**
Pressure (Pa)				
HA	-285.542 ± 248.60	-73.472 ± 95.13	212.062 ± 229.01	**< 0.001**
OA	-282.472 ± 249.90	-68.722 ± 95.87	213.742 ± 229.32	**< 0.001**
NA	-281.332 ± 249.26	-67.212 ± 97.61	214.122 ± 227.40	**< 0.001**
Nasal	-275.732 ± 246.42	-67.282 ± 97.75	208.452 ± 224.86	**< 0.001**
Velocity (m/s)				
HA	1.932 ± 1.05	2.252 ± 1.29	0.322 ± 0.88	0.205
OA	1.732 ± 0.69	1.952 ± 1.11	0.222 ± 1.03	0.534
NA	2.032 ± 1.23	1.782 ± 1.08	-0.252 ± 1.67	0.663
Nasal	18.602 ± 8.23	8.562 ± 5.03	-10.042 ± 5.74	**< 0.001**
Nasal Width (mm)				
Canine	20.522 ± 2.00	23.112 ± 2.53	2.592 ± 1.54	< 0.001
First Molar	31.352 ± 3.13	34.252 ± 2.89	2.912 ± 1.23	< 0.001
PNS	20.31 ± 2.61	31.61 ± 3.17	2.30 ± 1.29	**< 0.001**
Dental Width (mm)				
Canine	24.60 ± 1.73	27.37 ± 2.45	2.90 ± 1.63	**< 0.001**
First Molar	38.25 ± 2.24	42.22 ± 2.22	3.98 ± 2.23	**< 0.001**

**p-values determined using Wilcoxon signed-rank test.*

2.9. Polysomnography and OSA-18 Symptoms

Four of the 29 patients were excluded from the analysis due to the lack of post-treatment PSG. Twenty-five patients (16 males) completed pre- and post-treatment polysomnography (PSG) and the OSA-18 questionnaire (Tab. 1). All patients were previously treated by RPE with tooth anchored expanders. Sixteen patients had prior adenotonsillectomy. Nine of the patients that did not undergo adenotonsillectomy were deemed to have small tonsils (grade 1 or 2) that did not warrant surgery. The mean age was 13.16±1.46 years (range 10-16). The AHI improved from 6.72±4.34 to 3.59±5.11 ($p<0.001$) events per hour. The mean AHI reduction was 47% (range 20-79%). The minimum oxygen saturation increased from 92.72±2.21% to 93.89±1.20% ($p<0.05$). The interval between the preoperative PSG to TPD insertion was 9 months (range 2-24 months). Twenty-three of the twenty-five patients (92%) showed improvement based on PSG. In addition to improvement of PSG results, quality of life improvement was evident based on OSA-18 questionnaires (Tab. 1). All patients returned to school and regular activities within three days.

There were no adverse events related to the insertion of the TPD. Over-the-counter analgesics were used for pain control. Two patients had minor transient bleeding from the wound during the first week post-surgery, and the bleeding ceased spontaneously without intervention. During the expansion phase, displacement of the TPD was evident in two patients as one side of the TPD had migrated occlusally. The TPD was adjusted in the office setting under local anesthesia, and expansion continued without complications. All patients had a routine TPD removal in the office under local anesthesia.

2.10. Lateral Nasal wall and Dental width Changes

Nasomaxillary expansion was evident in all patients with separation of the midpalatal suture, nasomaxillary sutures, and the frontonasal sutures (Figs. 3 to 6). All of the patients had near parallel expansion pattern along the length of the nasal floor with sutural separation from ANS to PNS. The nasal sidewall widening was 2.59±1.54 mm at canine, 2.91±1.23 mm at first molar and 2.30±1.29 mm at PNS. The ratio of dental expansion to nasal expansion was 1.12:1 (2.90 mm:2.59 mm) at canine and 1.37:1 (3.98 mm:2.91 mm) at first molar.

2.11. CFD Pressure and Velocity

The mean airflow velocity in the nasal cavity significantly decreased by over 50% from 18.60±8.23 to 8.56±5.03 m/s (Tab. 1, Fig. 7). The airflow velocity did not change significantly in other parts of the pharyngeal airway. The mean negative pressure improved in the nasal airway (from -275.73±246.42 to -67.28±97.75 Pa), nasopharyngeal airway (from -281.33±249.46 to -67.21±97.61 Pa), oropharyngeal airway (from -282.47±249.90 to -68.72±95.87 Pa), and hypopharyngeal airway (from -285.54±248.60 to -73.47±95.13 Pa).

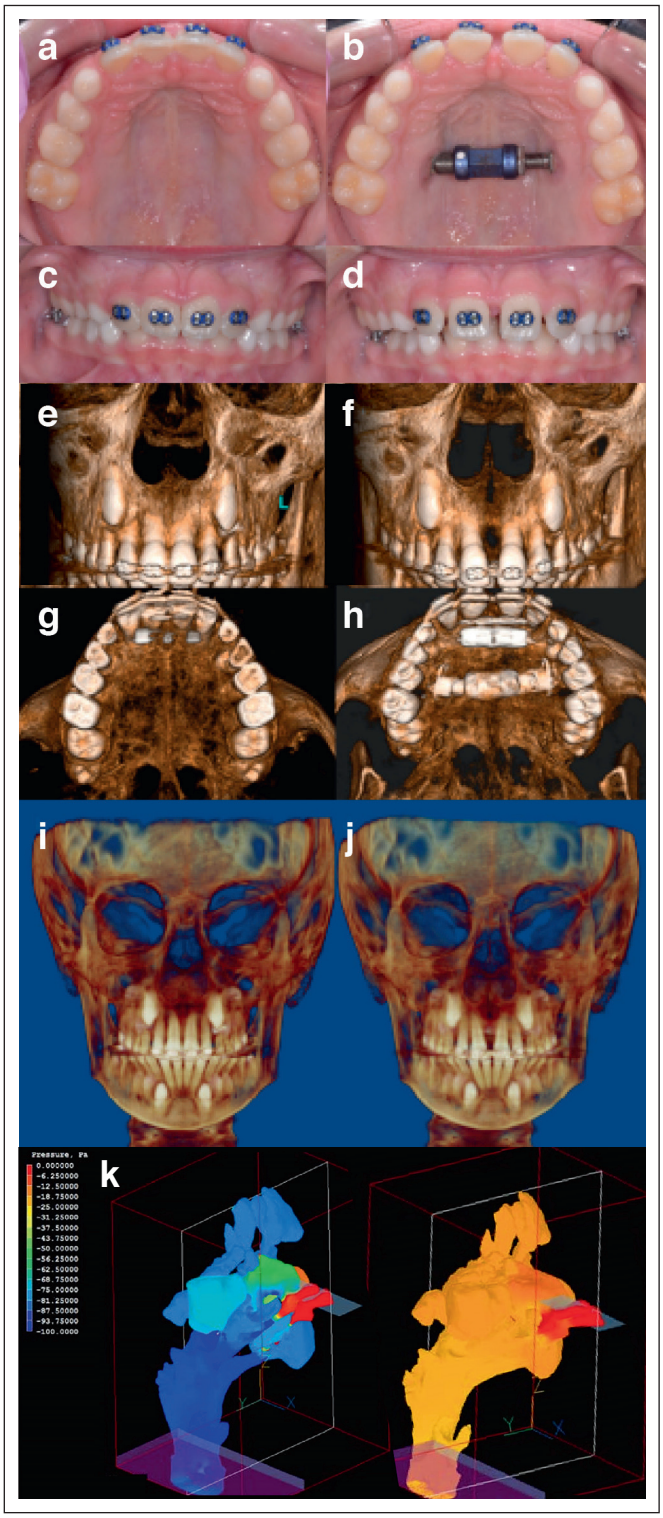

Figure 3

Nine-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) Pre- and postoperative CFD demonstrating airway pressure changes.

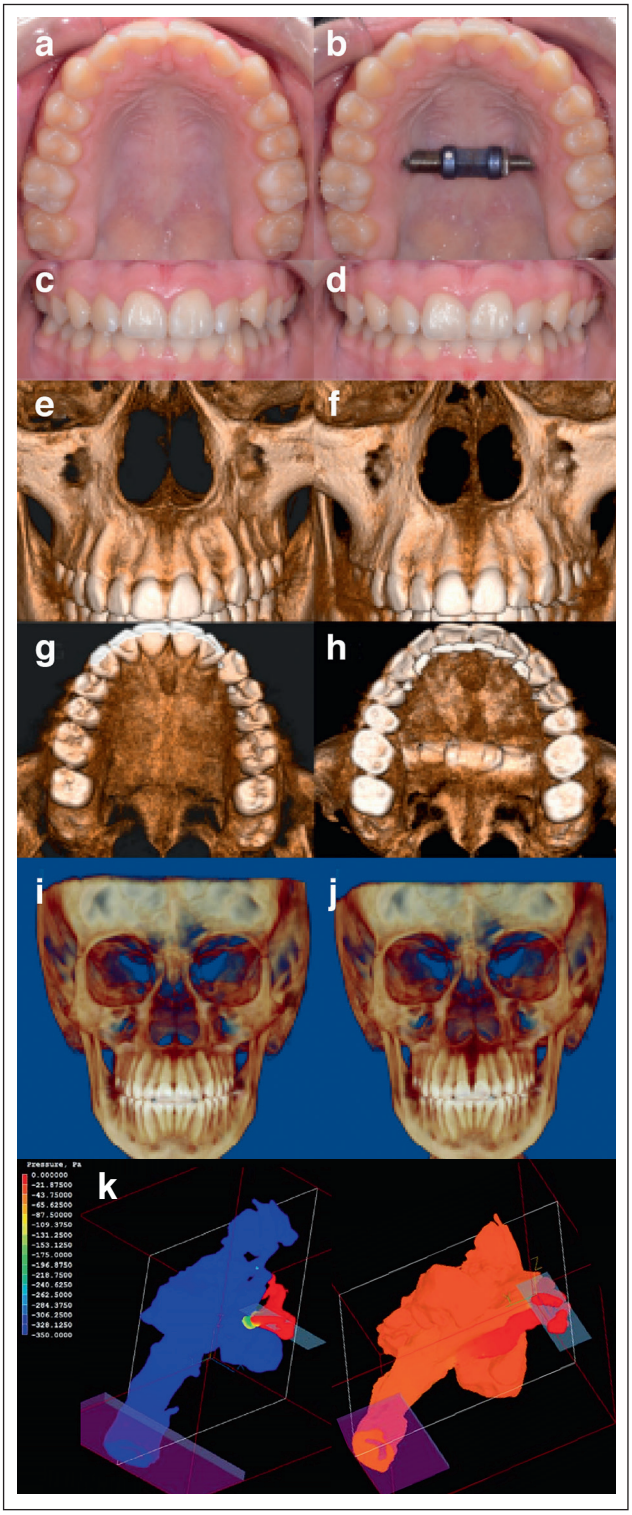

Figure 4

Twelve-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) Pre- and postoperative CFD demonstrating airway pressure changes.

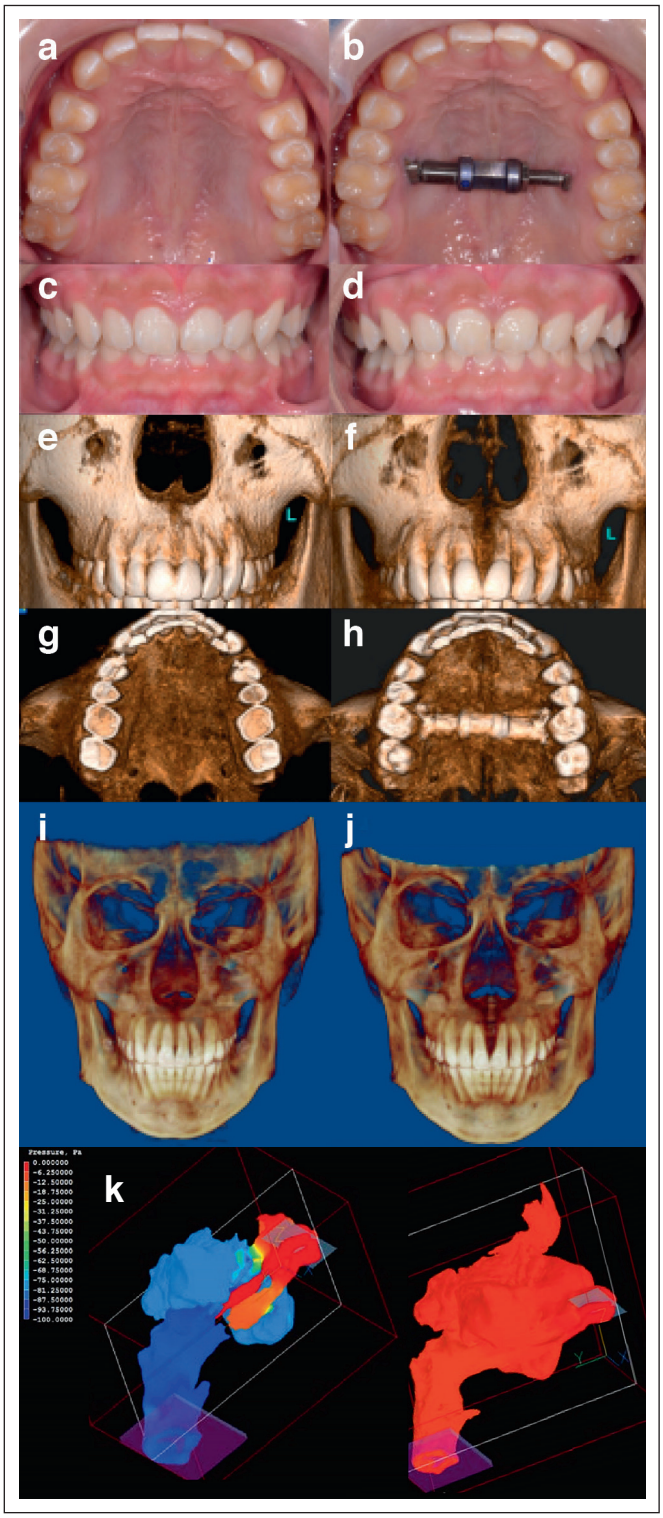

Figure 5

Thirteen-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) Pre- and postoperative CFD demonstrating airway pressure changes.

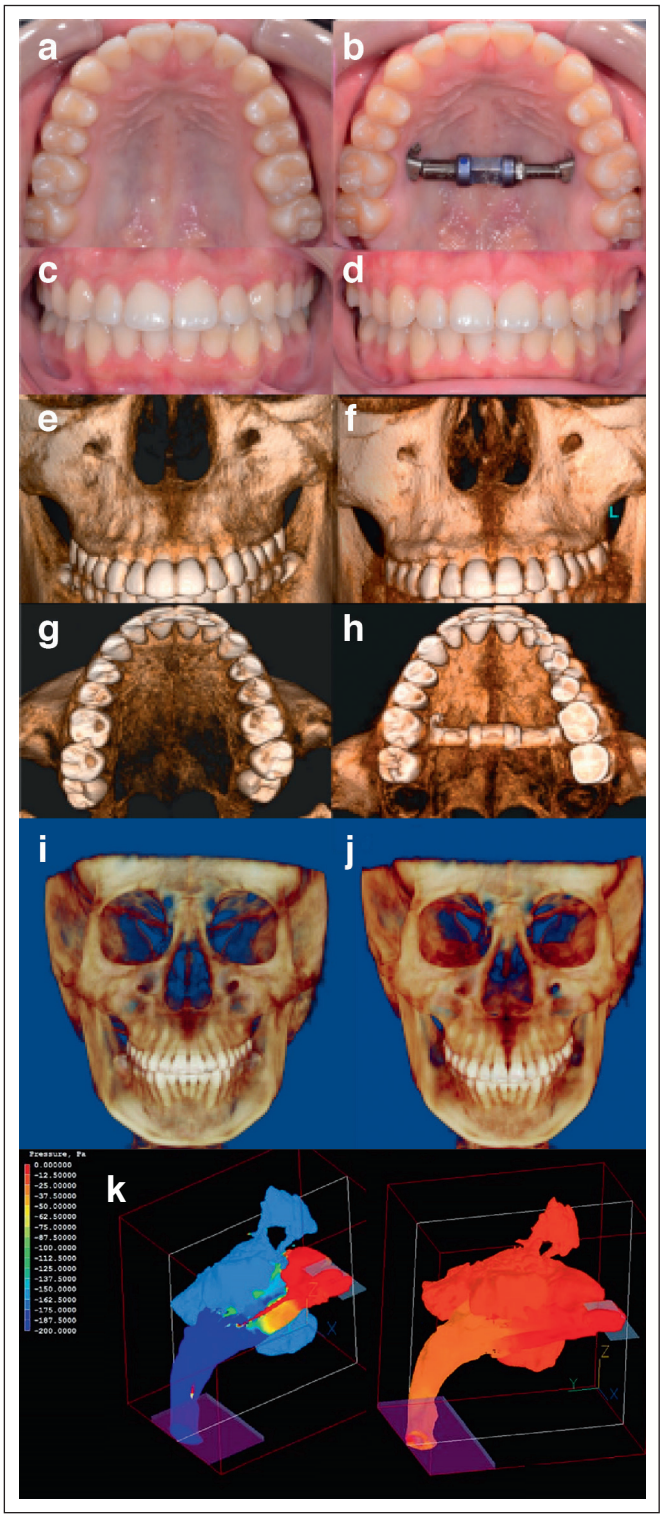

Figure 6

Fifteen-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) Pre- and postoperative CFD demonstrating airway pressure changes.

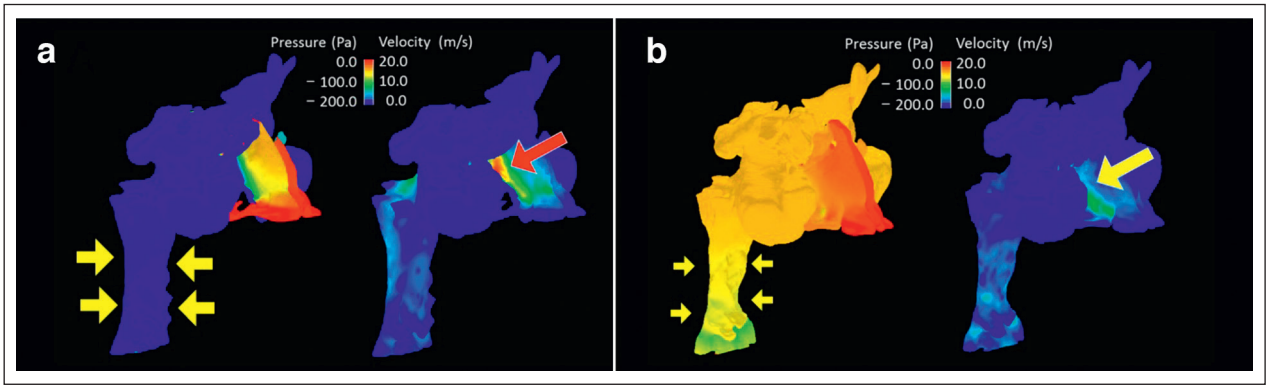

Figure 7

Change in upper airway ventilation modeled during inspiration by TPD. (a) Before TPD. *Right:* Computational fluid dynamics showing high nasal airway velocity (red arrow, more than 20m/s). The high velocity showed airway obstruction. *Left:* Maximal negative pharyngeal airway pressure is very high, resulting in a strong tendency to collapse the pharyngeal airway (large yellow arrow). (b) After TPD. *Right:* Computational fluid dynamics showed that nasal airway velocity is low (yellow arrow, less than 10 m/s). The airway obstruction site was improved. *Left:* The high negative pressure disappeared, resulting in improved airway collapsibility and corresponding reduced AHI values.

3. Discussion

This study highlights the persistence of OSA in a treated pediatric population as it is well recognized that OSA often remains with continual symptoms despite undergoing treatment such as adenotonsillectomy[1,14,15]. The children in this study are challenging to treat because commonly available treatment options such as adenotonsillectomy and RPE have already been utilized. Positive airway pressure therapy has limitations because it can be difficult to tolerate, but more importantly, long-term use can result in midface hypoplasia[22,37] which can potentially exacerbate or perpetuate airway resistance. Maxillofacial jaw advancement surgery is a later stage option that is not appropriate until jaw growth has ceased. Additionally, many families do not want to consider such an invasive procedure. Due to the lack of good remaining treatment options, we elected to treat these children with further maxillary expansion to improve nasal airflow, despite the lack of maxillary narrowing. While watchful waiting has shown an improvement of OSA in some primarily nonobese pediatric cohort (AHI< 5)[26], we are describing a different pediatric group that still present with residual mild OSA after therapies, and significant symptoms that prompted the families to seek further treatment.

Pediatric OSA treatments can be directed to decrease nasal resistance and establish nasal respiration because nasal resistance accounts for 50% of total airway resistance in both children and adults[9]. We elected to treat these patients with further maxillary expansion, despite the lack of maxillary narrowing and no other overt anatomical deficiencies. Orthodontic maxillary expansion has been a commonly employed pediatric treatment by our group to enlarge the upper airway. A clear distinction must be made as to what part of the upper airway is targeted and where the expansion actually occurs. Nasomaxillary expansion for OSA targets nasal cavity expansion. Intraoral dental expansion without nasal widening does not reduce nasal resistance. The ideal expander design would widen the lateral nasal walls to enlarge the nasal airway and the nasal widening would at least equal to, if not to a greater extent than the intraoral dentoalveolus. This is especially important in patients without maxillary constriction or crossbite, such as in patients previously treated with RPE, where the creation of a large diastema with excessive dental widening may lead to periodontal compromise and compromised esthetics and a significant malocclusion.

Airflow modeling based on CFD demonstrated elevated nasal airway velocity and negative pressure that suggest increased nasal resistance despite prior maxillary expansion. Higher nasal airway velocities have been described in cases of nasal blockage[21] as airway obstruction will create

higher airflow velocities. Airflow modeling further demonstrated a dynamic change in nasal airway pressure and velocity after TPD expansion. We postulate that the reduction of nasal airway resistance from expansion can render the airway less collapsible to the negative intraluminal pressure on inspiration, leading to reduced OSA severity, and this was reflected in improved negative airway pressure in the oropharyngeal and hypopharyngeal airway.

Numerous expanders are currently used, either skeletally anchored, tooth anchored or hybrid devices. A fundamental difference is emphasized between the types of maxillary expansion and the age at the time of expansion. Tooth anchored expanders are routinely used in RPE in young children for dental crowding and now for OSA. A review of 17 pediatric expansion studies showed that RPE is done at a mean age of 7.6 years for OSA treatment[4]. Enlarging the nasal airway by maxillary expansion becomes more difficult in older children due to maturation of the midpalatal suture where ossification occurs with resultant mineralized bridges[30], causing increased resistance to suture separation[27]. The concomitant dental widening precludes further skeletal expansion as the teeth move at a faster rate than the maxillary skeleton, in a ratio of about 3:1 in older adolescents and 2:1 in younger children during the deciduous or mixed dentition[7]. In patients without maxillary constriction or crossbite, such as in patients previously treated with RPE, the creation of a large diastema with excessive dental widening may lead to periodontal problems, compromised esthetics and a significant malocclusion. Skeletally anchored devices bypass the dentition with less tooth tipping because forces are directly applied on the palatal bone instead of the teeth to induce mid-palatal suture separation. Using TPD expansion yielded more efficient expansion at a ratio of dental to skeletal expansion of 1.37 (1st molar):1, demonstrating a more efficient skeletal nasal cavity expansion.

This study suggests that skeletally anchored TPD achieves a more favorable and predictable widening of the lateral nasal walls throughout the nasal airway. The extent of skeletal expansion compares favorably to other techniques[23,24,29]. It is apparent that forces applied by TPD in the posterior maxilla enable the separation of the entire length of midpalatal suture, even in the posterior region that is most resistant to expansion[8,33], thus enabling greater nasal airway expansion. Compared to RPE, TPD expansion resulted in a greater degree of lateral nasal wall expansion, less tooth movement while yielding a greater reduction in nasal airway pressure (76% vs 46%[17]). Based on the results of this study with the possibility of persistent OSA following maxillary expansion by RPE and the efficiency of airway expansion with TPD, we suggest that skeletally anchored expansion may be considered as a first line expansion method when the goal is nasomaxillary expansion for the treatment of OSA.

Finally, despite further nasal cavity expansion to reduce nasal resistance and improve upper airway collapsibility, OSA was improved in most of the children, but not fully resolved in any of the children. Furthermore, 8% of the children showed no improvement based on PSG. While nightly respiratory disturbances improved, the disorder persisted despite symptomatic improvement. This is the opposite outcome of the CHAT study where there was resolution of OSA but no symptomatic improvement with watchful waiting[26]. The multifactorial nature of the OSA syndrome may account for the residual OSA and the continued search for strategies to not only enlarge the upper airway but to also improve the neurosensory/neuromotor response.

The limitations of this study were the small sample size, and lack of a control group as this is a retrospective study. The retrospective approach limited our ability to obtain posttreatment PSG in four patients, which was due to insurance denial for PSG coverage. This might have been avoided if the study was conducted prospectively. Another limitation is that the study does not characterize changes in nasal cavity volume and nasal transport phenomena that might address nasal airway resistance. Nasal resistance was not measured and was not simulated with CFD. Data showing this relationship would help to validate further the CFD model used to calculate airflow values. However, it should be recognized that although the use of CFD to simulate airway dynamics is commonly used, it is merely a simulation and not a real-time airway study, thus any conclusion solely based on the result of CFD should be cautioned. Future work is needed at defining the optimum parameters of expansion (the amount and the rate) for each

patient and analyzing further resistance transport phenomena.

4. Conclusions

This study suggests that skeletally anchored distraction improves OSA in children with persistent or recurrent OSA previously treated by RPE. TPD achieves significant expansion of the nasal airway with a small residual diastema and a limited increase in maxillary dentoalveolar width, which are all important considerations in patients without maxillary constriction. The nasal airway expansion resulted in improved airflow dynamics as modeled by CFD analysis that correlated with improvement of OSA. This underscores the importance of early comprehensive multimodal treatment of pediatric sleep disordered breathing as residual symptoms and abnormal respiratory values persisted after prior therapy, highlighting the crucial role of the orthodontist in treating pediatric OSA.

Links of interest

The authors declare that they have no interest in the data published in this article.

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Original article

Maxillomandibular Advancement for OSA: Serious Complications and Failures

Kasey LI[1*], Christian GUILLEMINAULT[2]

[1] Sleep Apnea Surgery Center, 1900 University Avenue, Suite 105, East Palo Alto, CA, USA
[2] Deceased. Sleep Medicine Division, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA

KEYWORDS:
Maxillomandibular advancement / Bimaxillary advancement / MMA / Sleep apnea / DOME / OSA / Sleep surgery

ABSTRACT – Objective: *The focus of this report was to analyze patients who presented for second opinion due to complications and failure following maxillomandibular advancement (MMA) performed elsewhere.* **Materials and Methods:** *During a five-year period, 16 patients presented with complications and/or failure of MMA. The indication for treatment was obstructive sleep apnea (OSA). Analysis of treatment records including plane radiography and/or cone beam computed tomography (CBCT), progress photographs and clinical examination were performed.* **Results:** *Complete clinical and imaging records were available in all patients for analysis. Thirteen patients were surgical failures with advancement ranging from -4 to 5 mm. Five of the 13 patients had limited advancement at the initial surgery, and eight patients had hardware failure that required removal with resultant retrodisplacement of the mandible. Due to complications occurring in 11 patients, additional surgery ranging from two to six additional procedures after the initial operation was required. The complications included hardware failure (ten patients) that led to bone segment displacement (eight patients), non-union of the maxilla (two patients), non-union of the mandible (eight patients), chronic facial and/or joint pain (five patients), facial nerve injury (two patients), complete anesthesia of the lip/chin (five patients) and severe malocclusion (four patients).* **Conclusions:** *Although MMA is typically a predictable operation with excellent outcomes, failure of improvement and severe long-term sequelae from surgical complications are possible. Surgical precision with sufficient skeletal advancement for airway improvement and stable skeletal fixation is necessary to achieve a successful outcome.*

* Correspondance : drli@sleepapneasurgery.com

1. Introduction

Since the report of improved obstructive sleep apnea (OSA) following mandibular advancement in 1979[2], skeletal advancement surgery has evolved from a last stage operation of the phased surgical protocol to the primary, single stage maxillomandibular advancement (MMA) in properly selected patients. Over the past 25 years, the authors have extensively studied the relationship between the airway and maxillofacial skeleton. More importantly, the principles of maximizing skeletal advancement in improving OSA, maintaining proper facial balance and occlusion while minimizing complications have been established[1,3-21]. As the operation became widely performed, an increasing number of patients have presented for second opinion and management due to surgical complications and failure. The aim of this report was to analyze the surgical results of these patients to understand the factors that contributed to poor outcomes.

2. Materials and Methods

During a five-year period, 16 patients presented with complications and/or failure of MMA in improving OSA. Analysis of treatment records including plane radiography and/or cone beam computed tomography (CBCT), progress photographs, and clinical examination were performed to understand factors contributing to poor results. The outcomes were assessed as either failure in improving OSA and/or surgical complications that required additional operations and resultant long-term sequelae.

3. Results

Complete clinical and imaging records were available in all 16 patients for analysis. The group consisted of four women and 12 men with a mean age of 37.9 years (range 15-50 years). Thirteen patients were surgical failures with the final advancement ranging from -4 to 5 mm. Five of the thirteen patients had limited advancement at the initial surgery, and eight patients had hardware failure that required removal with resultant retrodisplacement of the mandible. Due to complications occurring in 11 patients, further surgery ranging from two to six additional procedures after the initial operation was necessary. The complications included hardware failure (ten patients) that led to bone segments displacement (eight patients), non-union of the maxilla (two patients), non-union of the mandible (eight patients), chronic facial and/or joint pain (five patients), facial nerve injury (two patients), complete anesthesia of the lip/chin (five patients) and severe malocclusion (four patients).

4. Case Reports

4.1. Case n° 1

A 44-year-old man with severe OSA underwent MMA after failed uvulopalatopharyngoplasty (UPPP). The operation was uneventful, with a reported 10 mm skeletal advancement. Due to persistent OSA symptoms, the patient presented for evaluation and second opinion. Analysis of the imaging records demonstrated a 4 mm maxillomandibular advancement, resulting in insufficient airway improvement (Fig. 1).

4.2. Case n° 2

A 32-year-old man with moderate OSA underwent MMA. The operation was uneventful, with a reported 10 mm skeletal advancement. Due to persistent OSA symptoms, the patient presented for evaluation and second opinion. Analysis of the imaging records demonstrated a 3 mm maxillomandibular advancement, resulting in insufficient airway improvement (Fig. 2).

4.3. Case n° 3

A 31-year-old man with moderate OSA underwent MMA. The operation was uneventful, with a reported 10 mm skeletal advancement. Due to persistent OSA symptoms, the patient presented for evaluation and second opinion. Analysis of the imaging records demonstrated 3 mm maxillomandibular advancement (red arrows), resulting in insufficient airway improvement (Fig. 3).

4.4. Case n° 4

A 48-year-old woman with moderate OSA underwent MMA. Due to multiple hardware failures and infections, the patient underwent six additional operations (Fig. 4). Unfortunately, the patient developed long-term facial and temporomandibular joint (TMJ) pain with difficulty in mastication and speech. The patient's OSA also worsened due to retrodisplacement of the mandible (-4 mm from baseline).

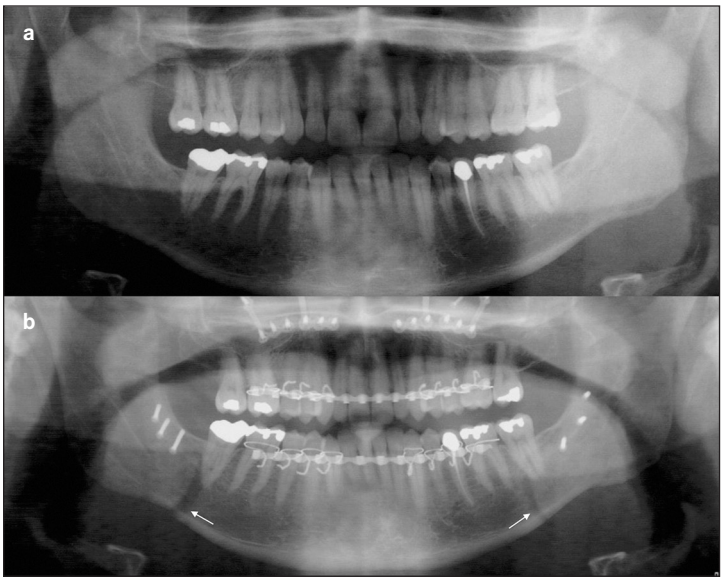

Figure 1
A 44-year-old man with severe OSA underwent MMA with a reported 10 mm skeletal advancement. (a) Preoperative panoramic radiograph. (b) Postoperative panoramic radiograph. Note the limited advancement (white arrows).

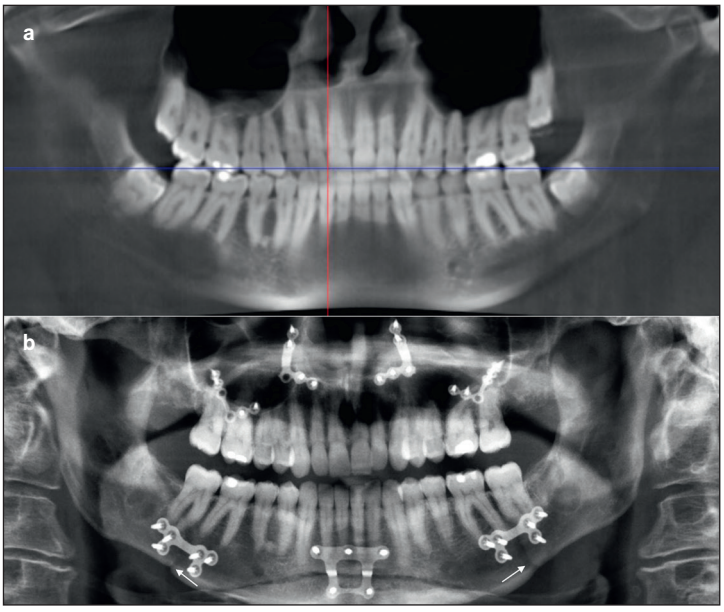

Figure 2
A 32-year-old man with moderate OSA underwent MMA and genioplasty with a reported 10 mm advancement. (a) Preoperative panoramic radiograph. (b) Postoperative panoramic radiograph. Note the limited advancement (white arrows).

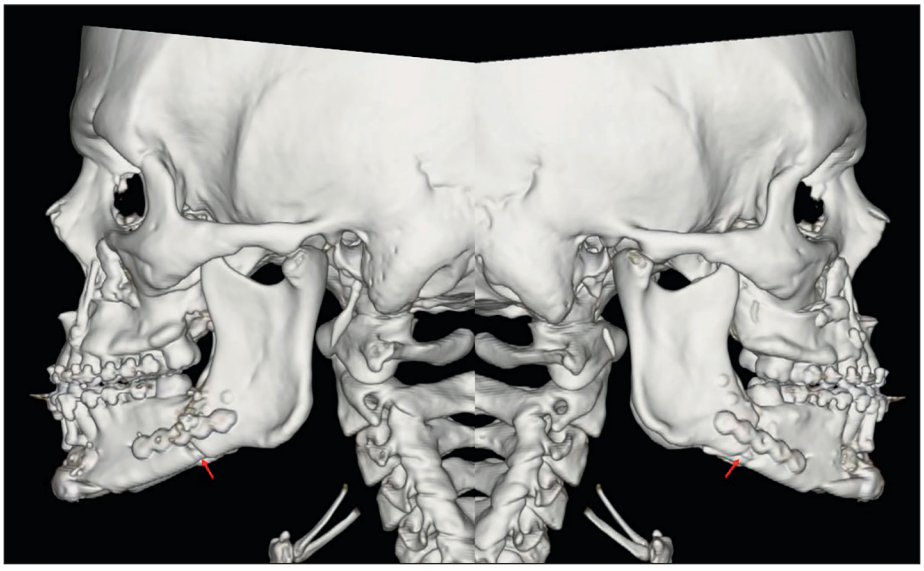

Figure 3
A 31-year-old man with moderate OSA underwent MMA and genioplasty with a reported 10 mm advancement. Note the limited 3 mm advancement (red arrows).

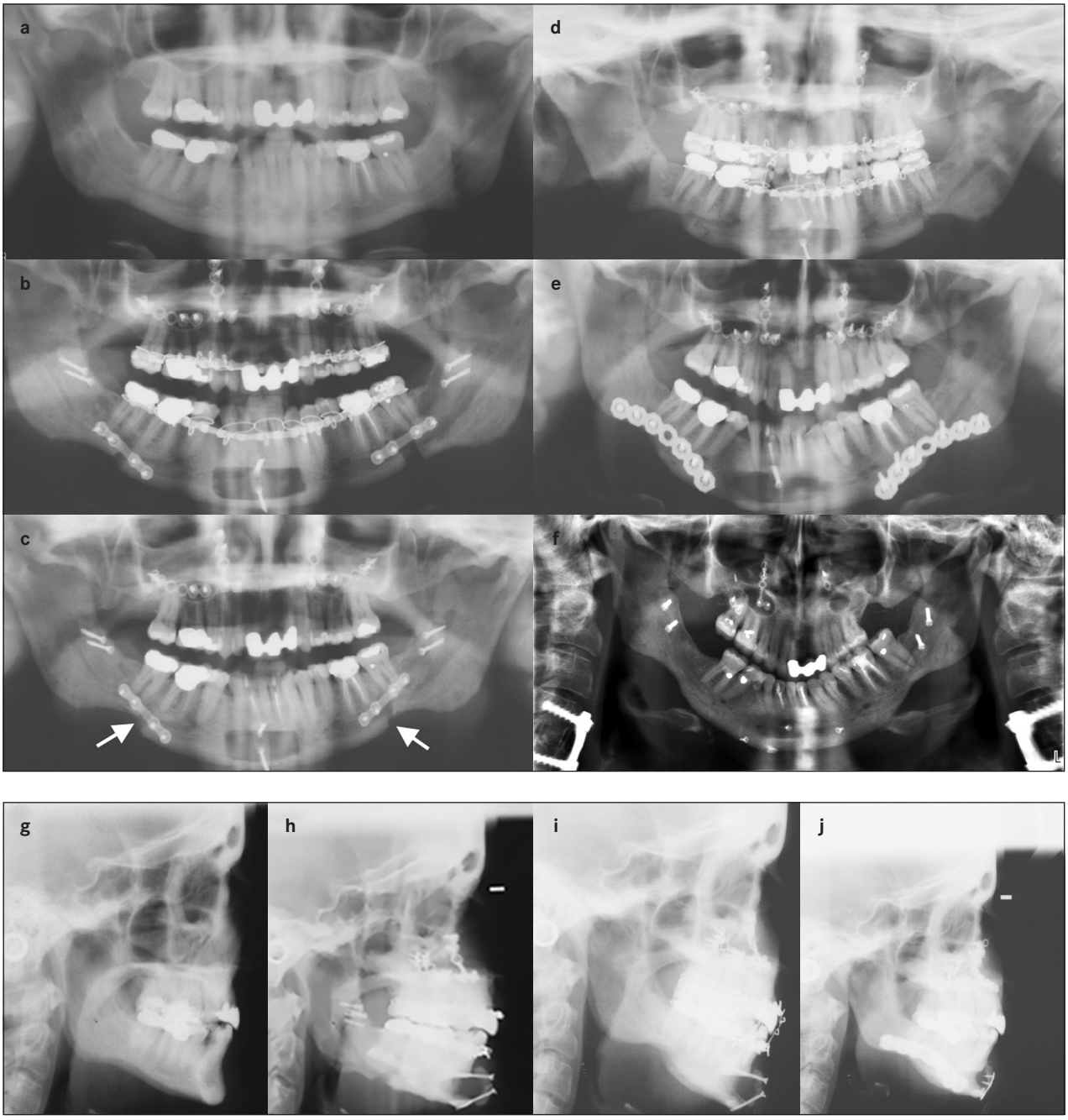

Figure 4

A 48-year-old woman with moderate OSA underwent MMA and genioglossus advancement. (a) Preoperative panoramic radiograph. (b) Postoperative panoramic radiograph. (c) Postoperative panoramic radiograph demonstrating bilateral hardware failure and mandibular displacement (white arrows). Note the endodontic treatment of the mandibular anterior teeth due to genioglossus advancement. (d) Panoramic radiograph demonstrating persistent infection necessitating mandibular hardware removal that resulted in bone segment displacement and retrodisplacement of the mandible. (e) Panoramic radiograph demonstrating rigid fixation of bilateral mandible with reconstruction plate. Note the revision surgery at the genioglossus advancement site due to persistent infection. (f) Panoramic radiograph demonstrating revision MMA due to continual non-union of the maxilla and the mandible. Note further revision surgery at the genioglossus advancement site. (g-j) Sequential lateral cephalometric radiograph demonstrating the mandible retrodisplaced 4 mm from baseline.

4.5. Case n° 5

A 36-year-old man initially requested MMA from the authors but was advised to continue positive airway ventilation treatment. The patient decided to proceed with MMA elsewhere. Due to hardware failure and infection, the patient underwent two additional operations after the initial MMA procedure. The patient presented for second opinion due to persistent mandibular pain and inability to masticate after three operations. The evaluation demonstrated pathologic fracture with continuity defect of the right mandible. The patient was subsequently lost to follow up (Fig. 5).

4.6. Case n° 6

A 45-year-old man with severe OSA underwent MMA. Due to multiple hardware failures and infections, the patient underwent hardware removal and subsequent mandibular reconstruction with iliac bone grafts via external approach.

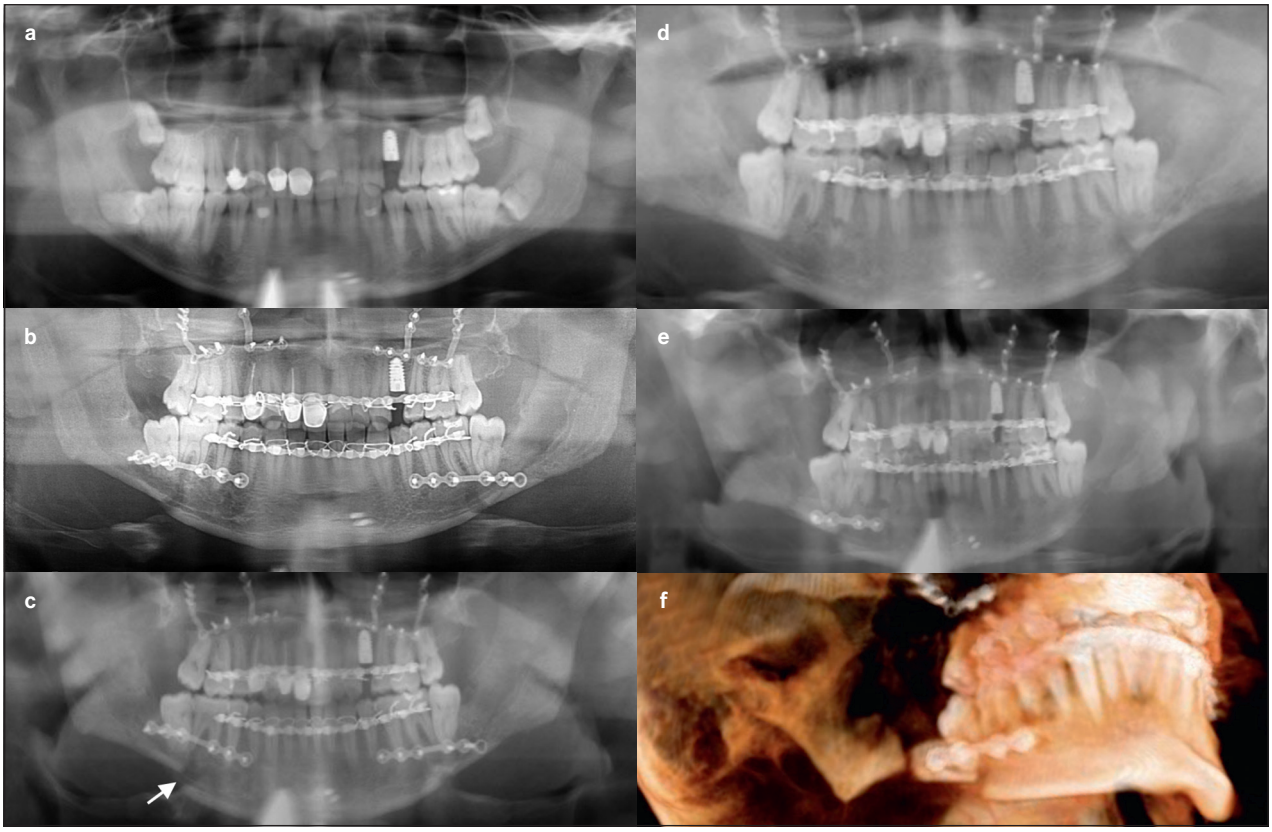

Figure 5

A 36-year-old man with severe OSA underwent MMA. (a) Preoperative panoramic radiograph. (b) Postoperative panoramic radiograph. (c) Postoperative panoramic radiograph demonstrating right mandibular hardware failure and mandibular displacement (white arrow). (d) Panoramic radiograph demonstrating persistent infection necessitating mandibular hardware removal with resultant bone segment displacement and retrodisplacement of the mandible. (e) Panoramic radiograph demonstrating rigid fixation to stabilize the right mandibular segments. Note the displaced bilateral mandibular proximal segments. (f) CBCT demonstrating a pathologic fracture proximal to the fixation plate, resulting in continuity defect of the mandible.

The patient presented for second opinion due to chronic pain of the mandible. No further surgery was advised, and the patient was referred to Neurology for chronic pain management (Fig. 6).

4.7. Case n° 7

A 30-year-old man with moderate OSA underwent MMA due to persistent symptoms following distraction osteogenesis maxillary expansion (DOME). The patient presented for second opinion with continual OSA symptoms. The evaluation demonstrated a 5 mm skeletal advancement, maxillary mobility, chronic infection involving the maxillary central incisors, and significant bone defect between the central incisor roots. The patient underwent endodontic therapy with guarded prognosis of the maxillary central incisors and is anticipated to undergo reconstruction for the maxillary non-union (Fig. 7).

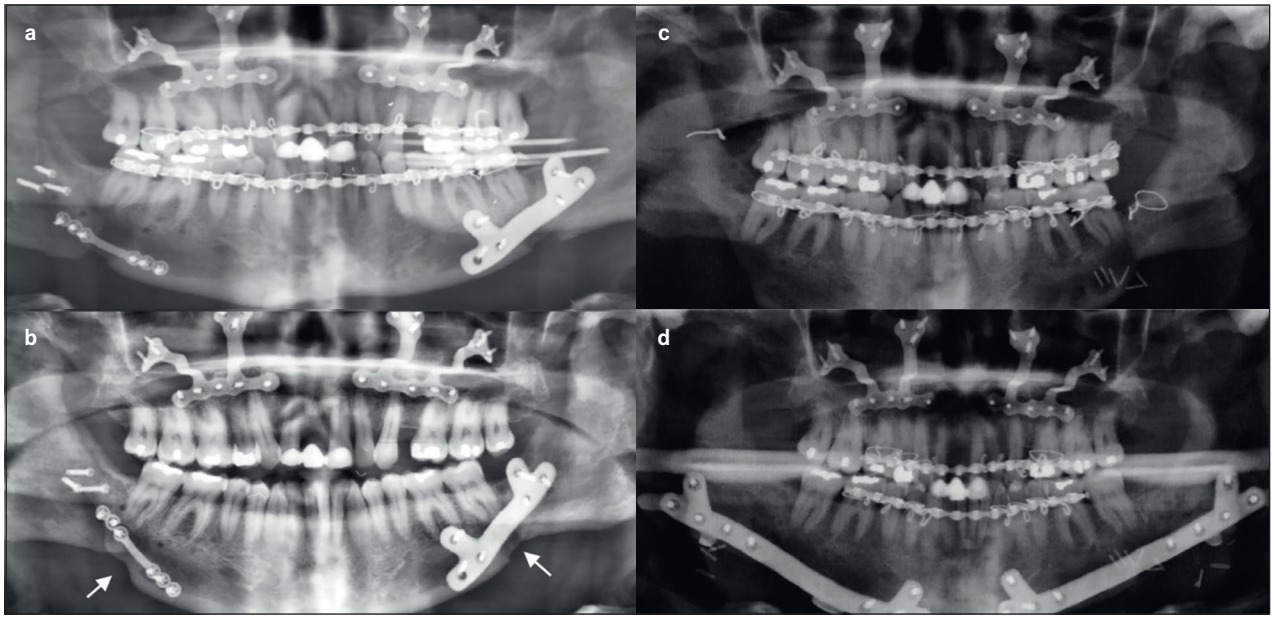

Figure 6

A 45-year-old man with severe OSA underwent MMA. (a) Postoperative panoramic radiograph. (b) Subsequent panoramic radiograph demonstrating bilateral mandibular hardware failure and mandibular displacement (white arrows). (c) Panoramic radiograph demonstrating hardware removal and further displacement of the mandibular segments. (d) Panoramic radiograph demonstrating bilateral mandibular reconstruction with iliac bone graft via external approach.

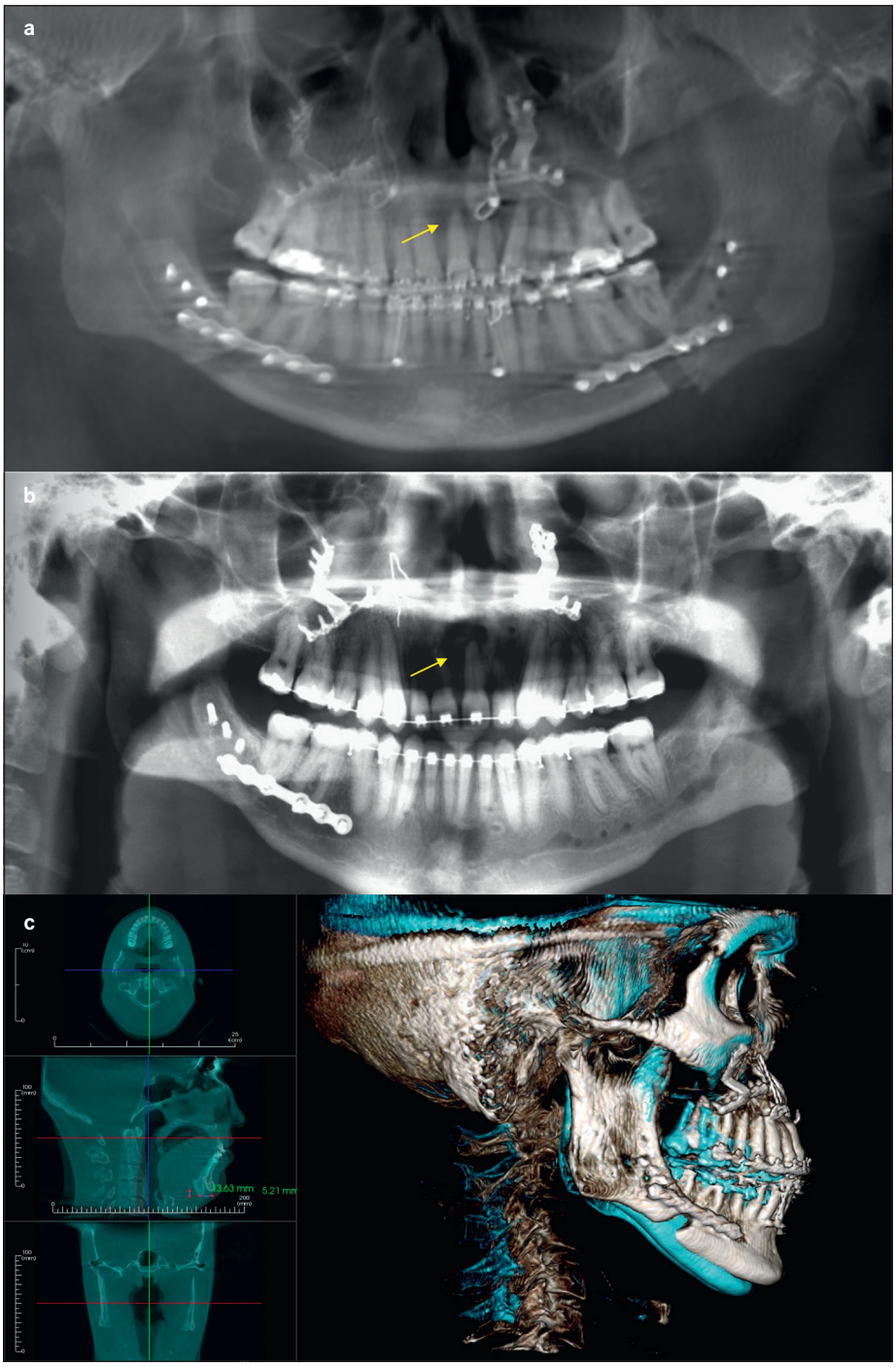

Figure 7

A 30-year-old man with moderate OSA underwent MMA due to persistent symptoms following DOME. (a) Postoperative panoramic radiograph. Note the large periapical radiolucency at tooth #9 (yellow arrow). (b) Postoperative panoramic radiograph demonstrating left mandibular hardware removal due to infection. Note the large periapical radiolucency at tooth #9 (yellow arrow). (c) CBCT demonstrating 50% of the advancement was from autorotation of the maxillomandibular complex that does not improve the airway. The effective skeletal advancement was 5 mm. The patient was noted to have a maxillary non-union and is anticipated to undergo reconstruction of the maxilla.

4.8. Case n° 8

A 45-year-old woman with moderate OSA underwent MMA and genioplasty. The patient developed facial and TMJ pain, absence of maxillary tooth show at full smile, and inability to close her lips. Subsequent surgery with maxillary hardware removal did not improve her symptoms, and the patient presented for second opinion. The evaluation demonstrated over-shortening of the maxilla due to excessive maxillary impaction, facial nerve injury, and mentalis muscle dysfunction. Revision maxillary surgery improved the maxillary tooth show, but facial pain and mentalis muscle dysfunction with lip incompetence persisted (Fig. 8).

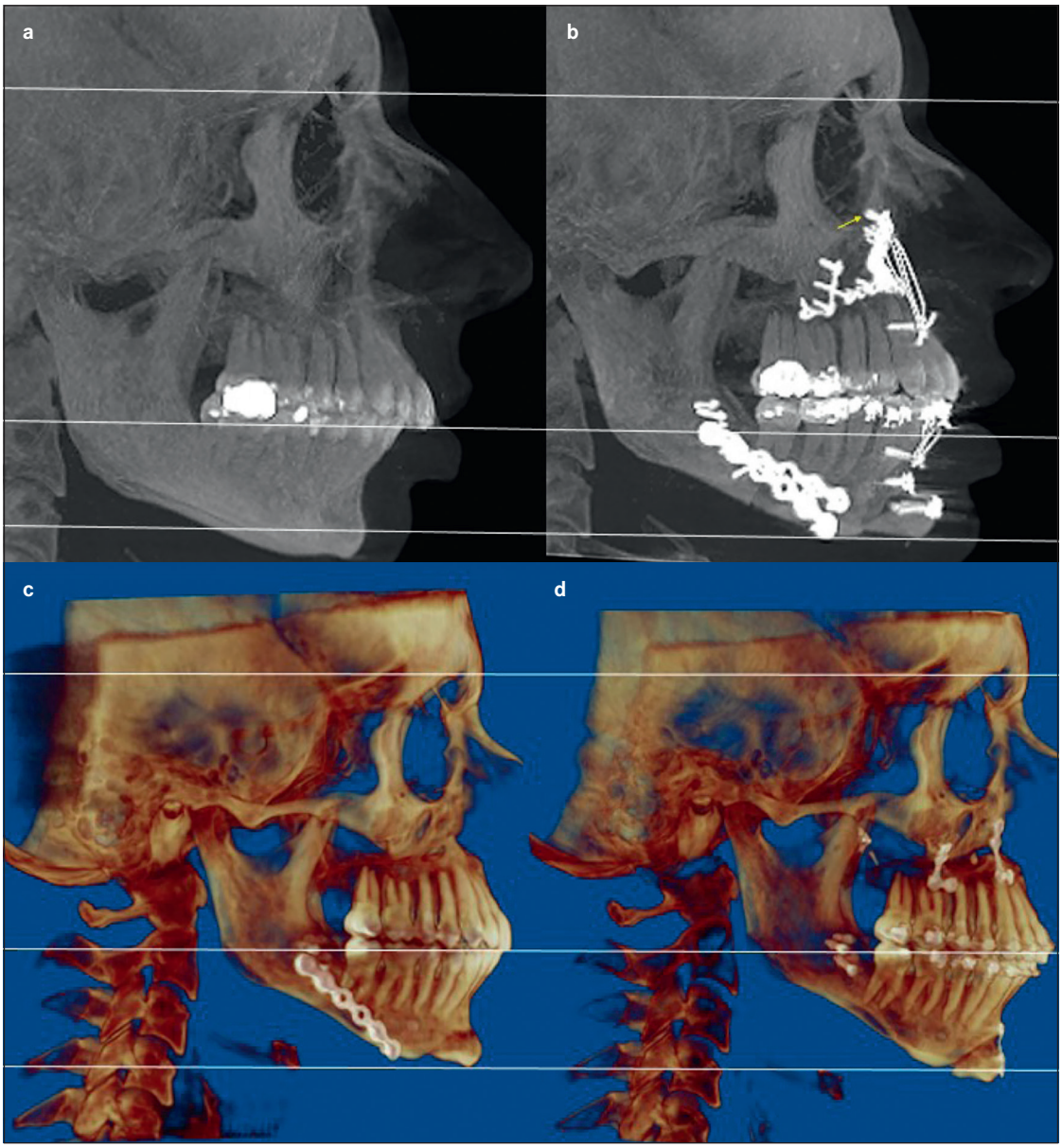

Figure 8

A 45-year-old woman with moderate OSA underwent MMA and genioplasty. The patient presented for second opinion due to facial and TMJ pain, absence of maxillary tooth show at full smile and inability to close her lips. (a) Preoperative lateral view. (b) Postoperative lateral view demonstrating excessive maxillary shortening. Note the maxillary plate/screws at the orbital rim. (c) The patient presented with second opinion with continual problems despite maxillary hardware removal. (d) Postoperative lateral view demonstrating revision maxillary surgery with bone grafting for maxillary lengthening. Revision genioplasty was also performed. The tooth shows improved but facial pain and mentalis muscle dysfunction with lip incompetence persisted.

4.9. Case n° 9

A 39-year-old man with moderate OSA underwent MMA due to failure of DOME, lingual tonsillectomy, nasal septoplasty, and turbinate reduction. The patient developed malocclusion postoperatively and presented for second opinion. The evaluation demonstrated bilateral mandibular non-union with infection on the left side.

The patient required two additional operations for mandibular debridement, fixation, and long-term intravenous antibiotics. Unfortunately, due to minimal bone contact due to the initial surgical design, the prognosis is guarded. Potential future reconstructive surgery with bilateral iliac crest bone grafting via external approach may be required when the infection resolution is assured (Fig. 9).

4.10. Case n° 10

A 30-year-old man with moderate OSA underwent MMA and genioplasty following failure of DOME, nasal septoplasty, and turbinate reduction. Due to bilateral mandibular infection, hardware removal and oral fistula closure was performed. The patient presented for second opinion with worsening malocclusion and return of OSA symptoms.

Evaluation demonstrated mandibular non-union that required debridement of necrotic bone and mandibular stabilization. Due to persistent OSA symptoms, the patient returned to positive airway therapy (Fig. 10).

5. Discussion

Despite the predictability and success of MMA in improving OSA, this report demonstrated that severe complications and failure are possible. Moreover, long-term sequelae due to complications can occur.

It is essential to maximize the advancement while taking consideration of the facial esthetics to enhance the success of MMA in improving OSA. Due to the impact of skeletal advancement on facial changes, the surgical plan must be a collaborative decision by the surgeon and the patient. Surgical precision is essential to minimize complications and ensure surgical stability. The osteotomy design and the fixation methods must be carefully planned as many of the complications reported were due to improper osteotomy technique and fixation failure. Proper adaptation of the plates and maximizing the bone contact between the mandibular segments are essential in orthognathic surgery. When large skeletal movement is performed to improve OSA, their importance cannot be overemphasized (Fig. 11). It was evident that despite the use of large plates for the mandibular fixation, failures occur. One must understand that regardless of the size of the plates/screws, a basic rigid fixation technique with precision plate adaptation must be performed since improper plate adaptation could cause displacement of the bone segments, leading to mandibular mobility, infection, and non-union, as demonstrated in this report.

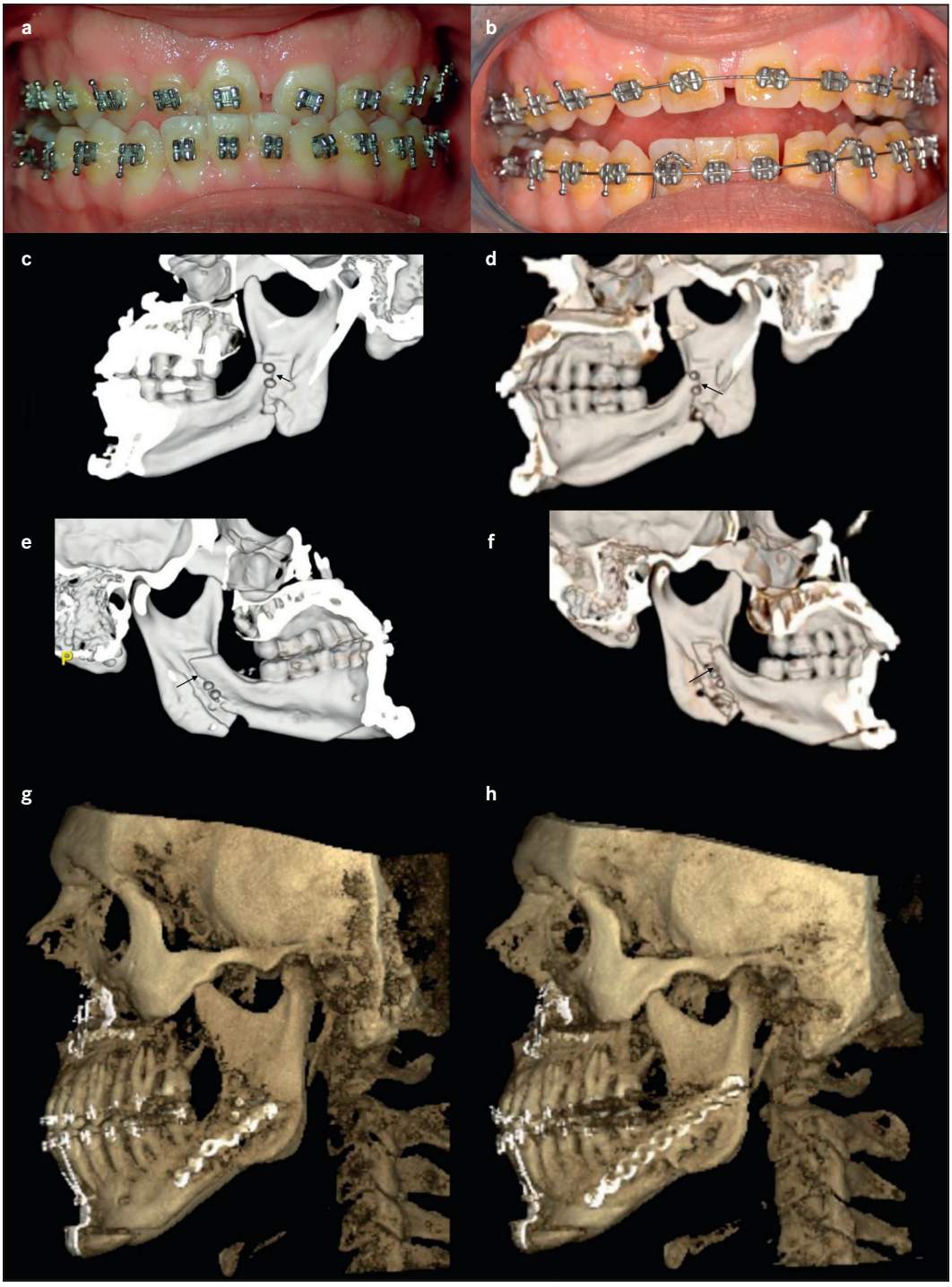

Figure 9

A 39-year-old man with moderate OSA underwent MMA due to failure of DOME, lingual tonsillectomy, nasal septoplasty and turbinate reduction. The patient developed malocclusion postoperatively and presented for second opinion. (a) Preoperative occlusion. (b) Postoperative occlusion upon presentation for second opinion. (c) Immediate postoperative CBCT demonstrating poor osteotomy design with inadequate bone overlap (black arrow). (d) CBCT upon presentation for second opinion. Note the displacement of the mandibular segments and bone resorption (black arrow). (e) Immediate postoperative CBCT demonstrating poor osteotomy design with inadequate bone overlap (black arrow). (f) CBCT upon presentation for second opinion. Note the displacement of the mandibular segments and bone resorption (black arrow). (g) CBCT upon presentation for second opinion for mandibular instability. (h) CBCT following debridement and fixation of mandibular segments.

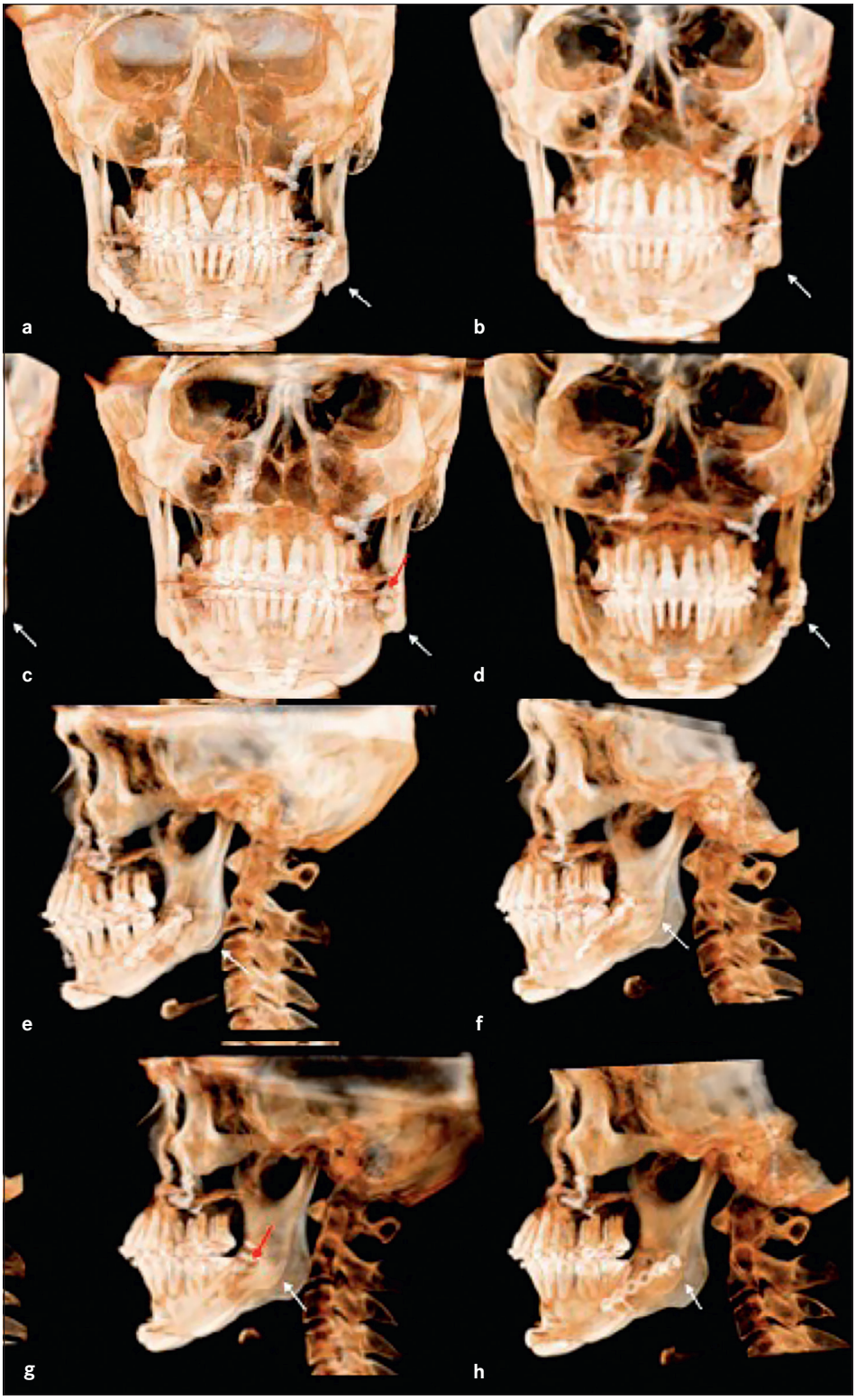

Figure 10

A 30-year-old man with moderate OSA underwent MMA and genioplasty due to failure of DOME, nasal septoplasty and turbinate reduction. The patient underwent a second operation for bilateral mandibular debridement, hardware removal and oral fistula closure. Due to malocclusion and worsening of OSA symptoms, the patients presented for second opinion. The patient was diagnosed with non-union of the mandible and underwent debridement of infected bone sequestrum and mandibular fixation. Sequential CBCT frontal (a-d) and lateral (e-h) images demonstrating infected bone sequestrum (red arrows) and mandibular displacement overtime (white arrows).

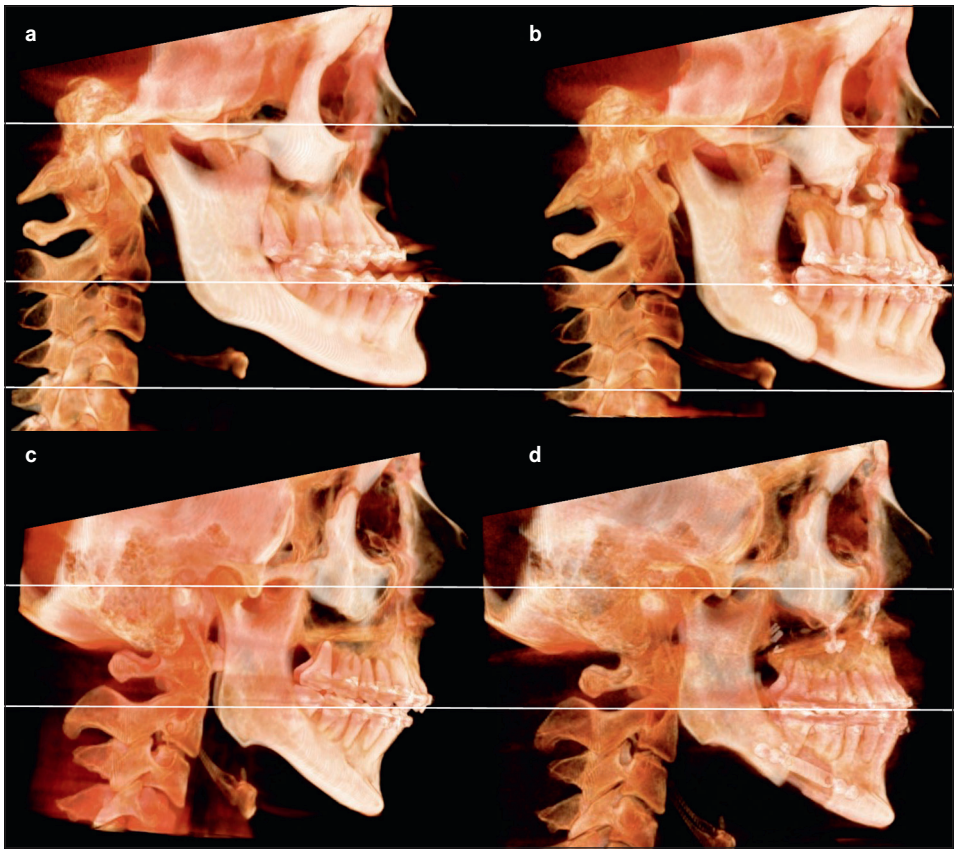

Figure 11

Two patients with distinctively different skeletal pattern that underwent MMA. The surgical design in advancement, rotation with occlusal plane and vertical dimension changes are vastly different but the principles of adequate bone overlap in osteotomy design to maximize fixation stability were maintained. (a) Preoperative image demonstrating maxillary deficiency and mandibular prominence in a patient with OSA. (b) Postoperative image demonstrating significant maxillary advancement and lengthening with mandibular advancement for airway improvement despite preoperative mandibular prominence. The postoperative facial esthetics was deemed satisfactory as per the patient because of the improved facial balance. (c) Preoperative image demonstrating maxillary and mandibular deficiency. (d) Postoperative image demonstrating maxillomandibular advancement with counter clockwise rotation of the skeletal complex and occlusal plane alteration.

6. Conclusion

Although MMA is typically a predictable operation with excellent outcomes, failure of improvement and severe long-term sequalae can occur. Understanding the surgical goal with sufficient skeletal advancement for airway improvement and precise surgical.

Links of interest

The authors declare that they have no interest in the data published in this article.

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Original article

Nasomaxillary Expansion by Endoscopically-Assisted Surgical Expansion (EASE): An airway centric approach

Kasey LI[1*], Tomonori IWASAKI[2], Stacey QUO[3], Eileen B. LEARY[4], Connor LI[1], Christian GUILLEMINAULT[5]

[1] Sleep Apnea Surgery Center, 1900 University Avenue, Suite 105, East Palo Alto, CA, USA
[2] Developmental Medicine, Health Research Course, Graduate School of Medical and Dental Sciences, Kagoshima University, 8-35-1 Sakuragaoka, Kagoshima 890-8544, Japan
[3] School of Dentistry, University of California San Francisco, 707 Parnassus Ave, San Francisco, CA 94143, USA
[4] Center for Sleep Sciences and Medicine, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA
[5] Deceased. Formally Sleep Medicine Division, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA

KEYWORDS:
OSA / EASE / TPD / SARPE / RPE / RME / MARPE / Maxillary expansion / Nasomaxillary expansion

ABSTRACT – Introduction: *The aim of this study was to analyze the skeletal, dental and airway changes with endoscopically assisted surgical expansion (EASE) to widen the nasomaxillary complex for the treatment of sleep apnea in adults.* **Methods:** *One hundred and five consecutive patients underwent EASE. Cone beam computed tomography (CBCT) was conducted preoperatively and within four weeks after the completion of the expansion process. Computational fluid dynamic (CFD) analysis was performed on 20 randomly selected patients to assess airway flow changes.* **Results:** *One hundred patients (67 males) with the mean age of 35.0±13.5 years (17-64 years) had completed pre- and post-expansion imaging. Ninety-six patients (96%) had successful expansion defined as separation of the midpalatal suture at least 1 mm from anterior nasal spine (ANS) to posterior nasal spine (PNS). The nasal cavity expansion was 3.12±1.11 mm at ANS, 3.64±1.06 mm at first molar and 2.39±1.15 mm at PNS. The zygoma expansion was 2.17±1.11 mm. The ratio of dental expansion to skeletal expansion was 1.23:1 (3.83 mm:3.12 mm) at canine and 1.31:1 (4.77 mm:3.64 mm) at first molar. CFD airway simulation showed a dynamic change following expansion throughout the airway. The mean negative pressure improved in the nasal airway (from -395.5±721.0 to -32.7±19.2 Pa), nasopharyngal airway (from -394.2±719.4 to -33.6±18.5 Pa), oropharyngeal airway (from -405.9±710.8 to -39.4±19.3 Pa) and hypopharyngeal airway (from -422.6±704.9 to -55.1±33.7 Pa). The mean airflow velocity within the nasal airway decreased from 18.8±15.9 to 7.6±2.0 m/s and the oropharyngeal airway decreased from 4.2±2.9 to 3.2±1.2 m/s. The velocity did not change significantly in the nasopharyngeal and hypopharyngeal regions.* **Conclusions:** *EASE results in expansion of the midpalatal suture from the ANS to PNS with a nearly pure skeletal movement of minimal dental effect. The expansion of the nasomaxillary complex resulted in the widening of the nasal sidewall throughout the nasal cavity. The improved air flow dynamics was demonstrated by CFD simulation.*

* Correspondance : drli@sleepapneasurgery.com

1. Introduction

Maxillary expansion is usually performed for the treatment of crossbite due to transverse maxillary deficiency. The use of maxillary expansion to treat obstructive sleep apnea syndrome (OSA) was first reported in 1998 in children and adults[5]. Over the past 20 years, numerous studies have documented the improvement of OSA with rapid palatal expansion (RPE) in children and surgically assisted rapid palatal expansion (SARPE) in adults[3,12,26,28,31,32]. The need of surgically assisted expansion approach in non-growing patients is justified due to the increased resistance to suture separation[25]. However, the expansion pattern between RPE and SARPE is different. RPE leads to a triangular opening in the frontal alveolar area where the apex of the expansion involves the nasal frontal suture[6], thus resulting in enlargement of the entire nasal vault. SARPE on the other hand, primarily widens the lower portion maxilla due to the Le Fort I osteotomy. By design, SARPE widens the maxillary alveolus and the nasal floor while exerting less impact on the nasal airway above the osteotomy, thus limiting the extent of the airway impact (Fig. 1).

Mini-screw assisted rapid palatal expansion (MARPE) has been advocated in recent years to achieve a greater skeletal expansion with improved skeletal anchorage. The expansion pattern of MARPE has been shown to involve the entire zygomaxillary complex[4,22,23,29], thus conceptually achieves a favorable expansion pattern when compared to SARPE (Fig. 1). However, the application of MARPE is primarily limited to teens and young adults. A systematic review of 264 MARPE patients showed an average age 12.3 years[17]. Additionally, although MARPE achieves a greater midpalatal suture opening as compared to conventional tooth-borne expanders, teeth tipping and dentoalveolar remains and the dental expansion still occurs in a considerably greater extent than skeletal expansion[17,20,23].

To apply maxillary expansion as a treatment for OSA to all adults, a surgical procedure named endoscopically-assisted surgical expansion (EASE) was developed in 2017[18]. The operation was designed as a minimally invasive procedure to create a favorable nasomaxillary expansion pattern by maximizing airway improvement while limiting teeth inclination and dentoalveolar expansion. Initial results demonstrated reduction of OSA severity along with improvement of subjective symptoms[18]. The aim of this study was to evaluate the skeletal, dental and airway changes with EASE based on cone beam computed tomography (CBCT) and computational fluid dynamics (CFD) analysis.

2. Materials and Methods

The data from one hundred and five consecutive patients that underwent EASE for the treatment of OSA were retrospectively reviewed. CBCT was conducted preoperatively and within four weeks after the completion of the expansion process. Additionally, CFD analysis was performed on 20 randomly selected patients to assess airway flow changes. This study was approved by IRB.

2.1. Surgical Procedure: endoscopically-assisted surgical expansion (EASE)

Surgery was performed by the same surgeon for all patients under either general anesthesia via oroendotracheal intubation or intravenous sedation. A small incision just behind the posterior tuberosity was made, and the pterygomaxillary suture was identified using a periosteal elevator. Gentle pterygomaxillary separation was achieved with a piezoelectric blade (DePuy Synthes, Switzerland). With the help of a nasal endoscope to visualize the nasal airway, a partial osteotomy was performed at the junction of the nasal septum and the nasal floor with the blade angled towards the midpalatal suture (Fig. 2). The depth of the osteotomy was planned based on the preoperative CBCT measurement. The osteotomy was performed bilaterally from the posterior nasal spine (PNS) to the greater palatine foramen (along the nasal floor). The ANS separation was achieved using a very thin osteotome via a stab incision between the maxillary incisors. A transpalatal distractor (TPD, KLS Martin Group, Jacksonville, FL) was inserted onto the palate at the region of the second premolar and the first molar. The TPD was fully engaged to the palatal bone and the foot plates of the TPD were stabilized with a 5 mm screw.

2.2. Expansion Process

The TPD was activated between 3 to 5 days after surgery by 0.1 to 0.3 mm per day. The expansion process is deemed complete when either the patient has experienced no further clinical improvement with continual expansion or when excessive buccal crossbite is present. Once expansion was completed,

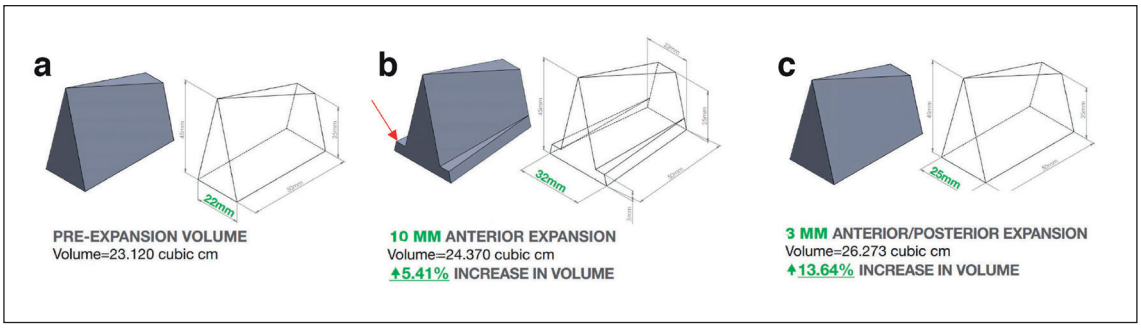

Figure 1

Solid modeling computer-aided design with SolidWorks®. (a) Hypothetical baseline nasal dimension. (b) Proposed 10 mm SARPE expansion pattern below the osteotomy (red arrow) without opening posteriorly. (c) Proposed 3 mm expansion with opening of the midpalatal suture anteriorly and posteriorly.

the TPD was locked and removed under local anesthesia three months later. Orthodontic treatment was initiated after the removal of the TPD.

2.3. Cone Beam Computed Tomography (CBCT)

All patients underwent CBCT preoperatively and within four weeks after the completion of the expansion. CBCT scans were acquired in the supine position in extended field modus (FOV: 16x22 cm, scanning time 2x20 s, voxel size 0.4 mm, NewTom 3D VGI, Cefla North America, Charlotte, NC). Data from CBCT were exported in Digital Imaging and communications in Medicine (DICOM) format into InVivo5® software (Anatomage, San Jose, CA, USA) and were reoriented with the palatal plane parallel to the floor in the sagittal and coronal planes. The following measurements were recorded by dental radiology technicians blinded to the study: intercanine width, nasal width at canine, intermolar width, nasal sidewall width at first molar, nasal sidewall width at posterior nasal spine and zygomatic width (Fig. 3).

2.4. Simulation of Airway Ventilation with Computational Fluid Dynamics (CFD)

Volume-rendering software (INTAGE Volume Editor, CYBERNET, Tokyo, Japan) was used to generate 3D volume data for the upper airway. Using mesh-morphing software (DEP Mesh Works/Morpher, IDAJ, Kobe, Japan), the 3D models were subsequently converted to a smoothed model without losing the patient-specific shape of the airway. CFD was used to simulate ventilation of the upper airway models (Fig. 4)[14,15]. The models were exported to fluid dynamics software (PHOENICS, CHAM-Japan, Tokyo, Japan) in stereolithographic format, and the fluid was assumed to be Newtonian, homogeneous, and incompressible. Elliptic-staggered equations and a continuity equation were used in the analysis. The CFD of the upper airway models was analyzed under the following conditions: volumetric flow rate of 7 ml/s/kg no-slip condition at the wall surface, and 300 iterations to calculate mean values. Convergence was judged by monitoring the magnitude of the absolute residual sources of mass and momentum, normalized to their respective inlet fluxes. The iteration was continued until all residuals fell below 0.2%. Simulation of estimated airflow pressure and velocity was performed at the nasal airway, nasopharyngeal airway (NA), oropharyngeal airway (OA), and hypopharyngeal airway (HA).

2.5. Statistical Analyses

Descriptive statistics and frequency distributions were performed on demographic and surgical characteristics. Means and standard deviations are reported for continuous variables, and number and percent for categorical variables. Data were evaluated for extreme or implausible values and missingness. The paired student's t-test was used to compare mean of the differences between the preoperative and postoperative samples. Difference in means was reported with 95% confidence interval. For the CFD data, the paired sample Wilcoxon signed-rank test was used due to the small sample size and skewed distribution of some measures. Analyses were performed using R Studio Version 1.1.463. A 2-sided p-value < 0.05 was used to indicate statistical significance.

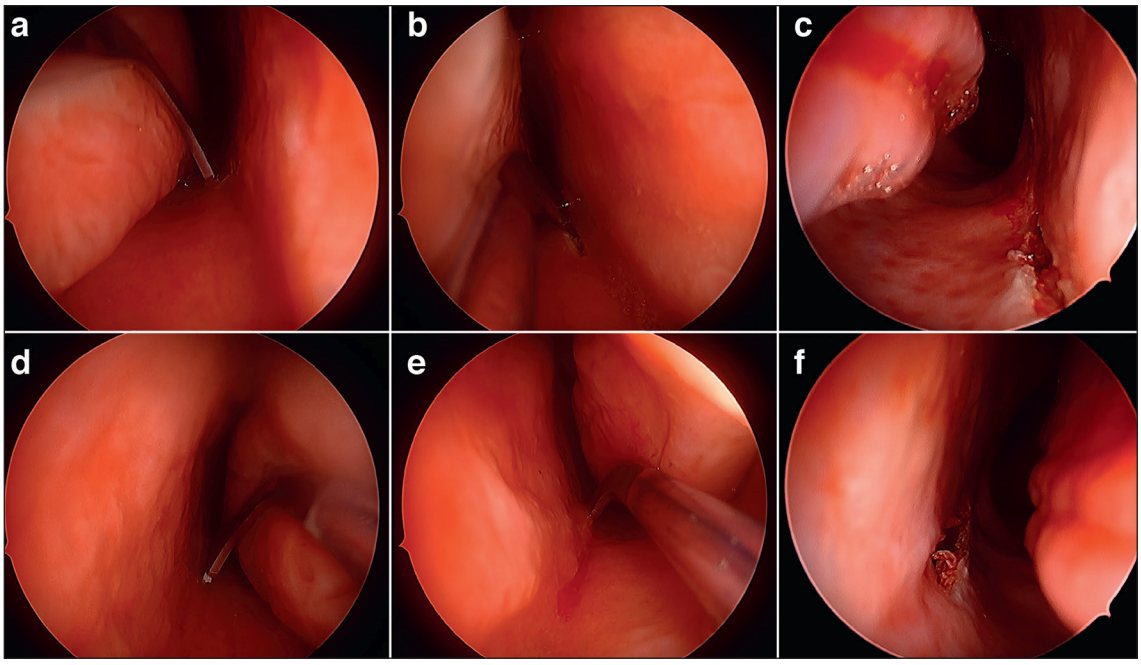

Figure 2

EASE procedure. (a) Piezoelectric blade at PNS in the right nasal cavity. (b) Osteotomy from the PNS. (c) Osteotomy completed. (d) Piezoelectric blade at the PNS in the left nasal cavity. (e) Osteotomy from the PNS. (f) Osteotomy completed.

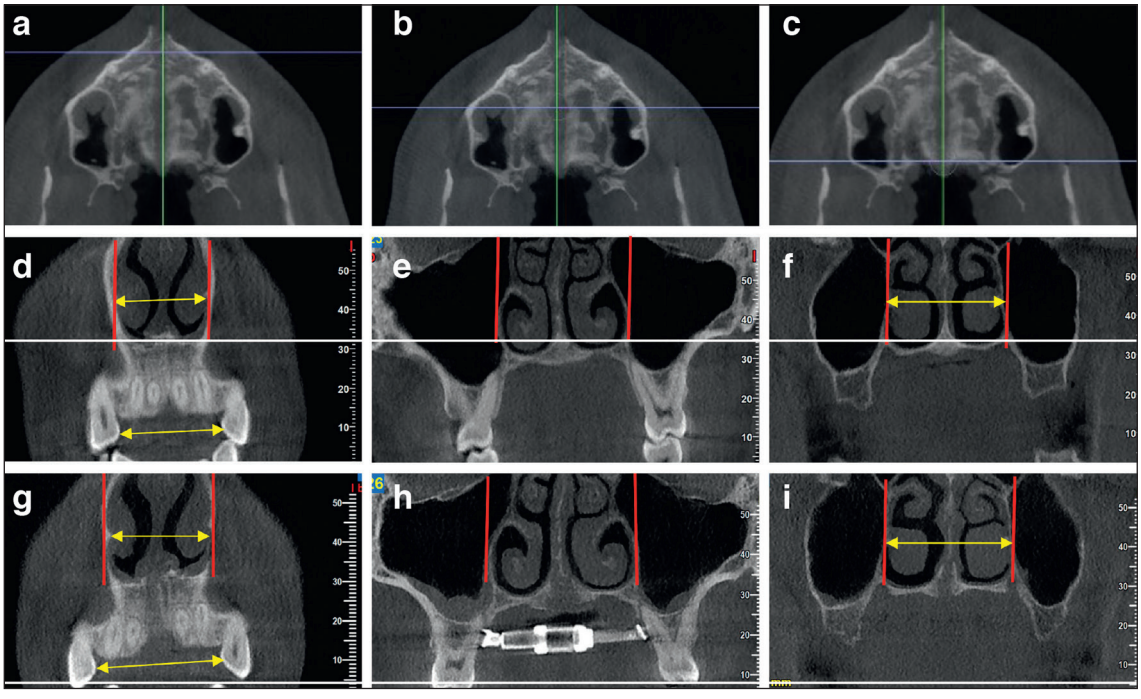

Figure 3

CBCT measurements. (a) Location of anterior measurement at canine. (b) Location of measurement at first molar. (c) Location of posterior measurement at PNS. (d) Frontal view of preoperative intercanine width and nasal width measurement. (e) Frontal view of preoperative intermolar width and nasal width measurement. (f) Frontal view of preoperative nasal width measurement at PNS. (g) Frontal view of postoperative intercanine width and nasal width measurement. (h) Frontal view of postoperative intermolar width and nasal width measurement. (i) Frontal view of postoperative nasal width measurement at PNS.

3. Results

One hundred and five consecutive patients underwent EASE. Five patients did not undergo post-expansion CBCT and were excluded from the analysis. One hundred patients (67 males) with the mean age of 35.0±13.5 years (17-64 years) had completed pre- and post-expansion imaging (Tables 1 and 2). Ninety-six patients (96%) had successful expansion defined as separation of the midpalatal suture at least 1 mm from anterior nasal spine (ANS) to posterior nasal spine (PNS). Two patients had separation of the ANS but not PNS and two patients did not have separation of the midpalatal suture. The nasal sidewall expansion was 3.12±1.11 mm at canine, 3.64±1.06 mm at first molar and 2.39±1.15 mm at PNS. The zygoma expansion was 2.17±1.11 mm. The ratio of dental expansion to skeletal expansion was 1.23:1 (3.83 mm:3.12 mm) at canine and 1.31:1 (4.77 mm:3.64 mm) at first molar. Ninety-six patients (96%) had a near parallel expansion pattern with opening of the ANS to PNS (Figs. 5 to 10).

CFD simulation was performed on 20 randomly selected patients (Table 1) to assess airway flow changes (Table 3). The mean airflow velocity within the nasal airway changed from 18.8±15.9 to 7.6±2.0 m/s and the oropharyngeal airway decreased from 4.2±2.9 to 3.2±1.2 m/s. The airflow velocity did not significantly change in the nasopharyngeal airway (from 3.0±3.1 to 2.2±1.1 m/s) or the hypopharyngeal airway (from 3.9±1.6 to 3.8±1.7 m/s). The mean negative pressure improved in the nasal airway (from -395.5±721.0 to -32.7±19.2 Pa), nasopharyngal airway (from -394.2±719.4 to -33.6±18.5 Pa), oropharyngeal airway (from -405.9±710.8 to -39.4±19.3 Pa) and hypopharyngeal airway (from -422.6±704.9 to -55.1±33.7 Pa).

4. Discussion

The nose is the most resistive element of the airway that accounts for 50% of the total airway resistance[11,27]. Hence, the objective of maxillary expansion is to maximize the enlargement of the nasal airway to diminish the resistance of nasal airflow. In an attempt to maximize nasal widening by SARPE, modified SARPE such as distraction osteogenesis maxillary expansion (DOME) has been advocated. DOME incorporated the use of mini-screws to improve skeletal anchorage along with over-widening of the maxilla (10+mm) in treating OSA patients[21,35]. However, the pattern of expansion remains the same for all forms of SARPE because Le Fort I osteotomy is incorporated. Moreover, excessive widening can lead to lack of bone fill in the maxillary alveolus and devitalization of the teeth thus resulting in long-term problems[19]. Indeed, severe complications related to SARPE, including loss of bone and teeth, have been previously reported[9,23].

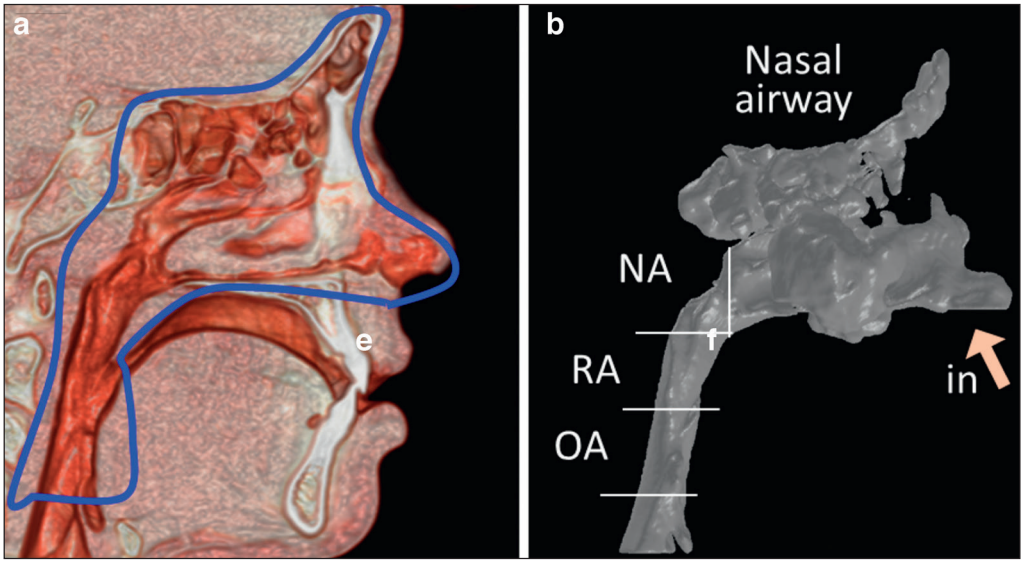

Figure 4

Evaluation of upper airway ventilation using computed fluid dynamics. (a) Extraction of the upper airway. (b) Construction of three-dimensional upper airway model and numeric simulation (inspiration air mass flow: 7 ml/s/kg), at nasopharynx (NA), oropharynx (RA) and hypopharynx (OA).

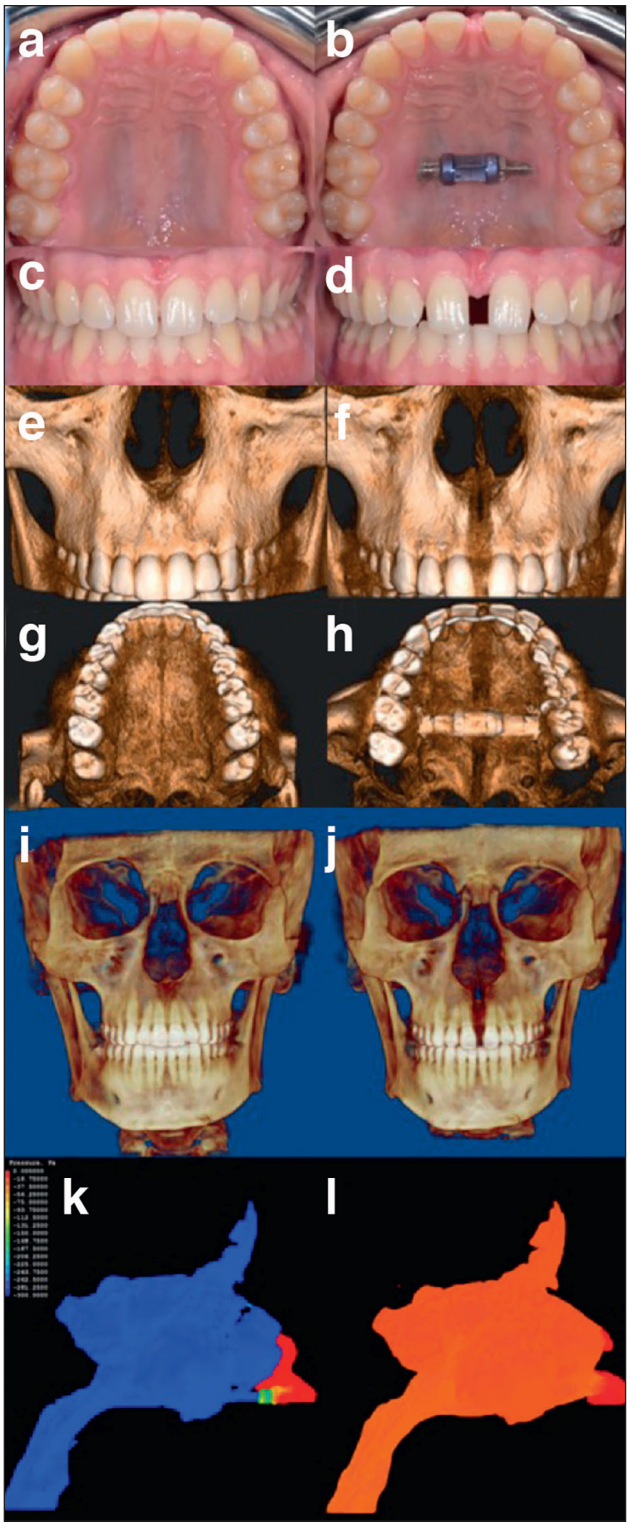

Figure 5

21-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) CFD showing preoperative airway pressures. (l) CFD showing postoperative airway pressures.

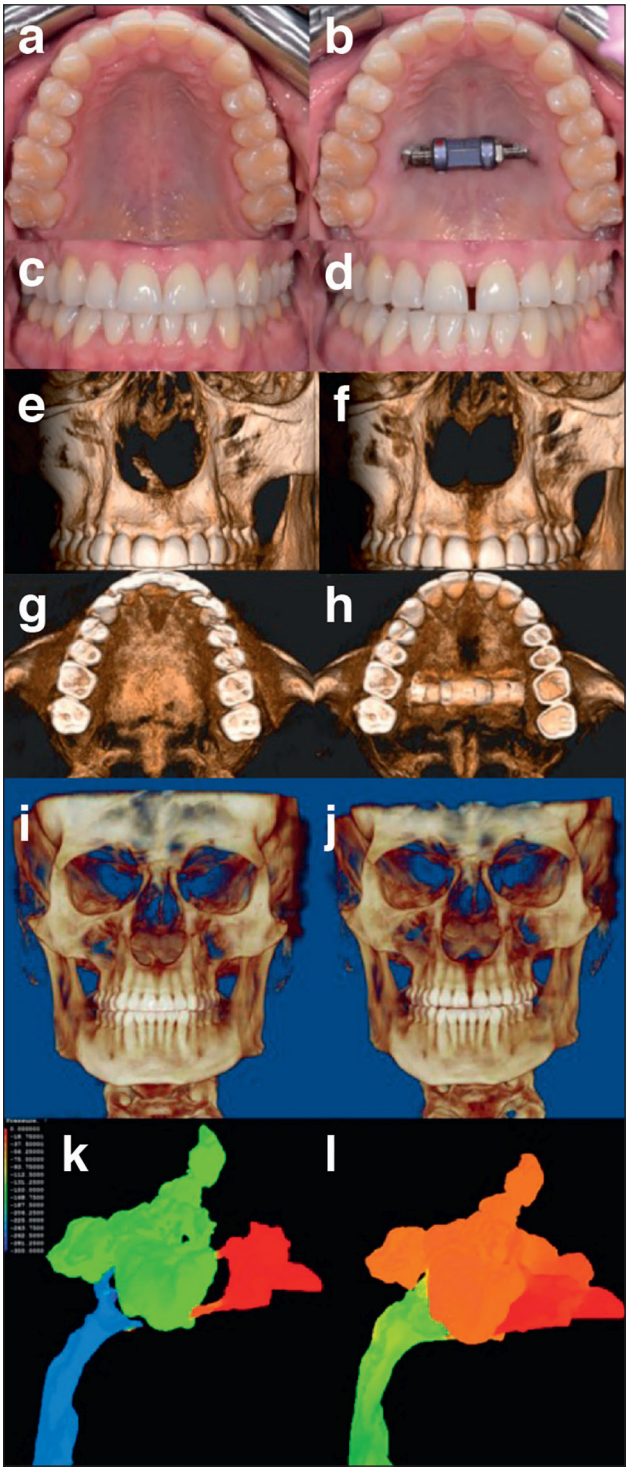

Figure 6

28-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) CFD showing preoperative airway pressures. (l) CFD showing postoperative airway pressures.

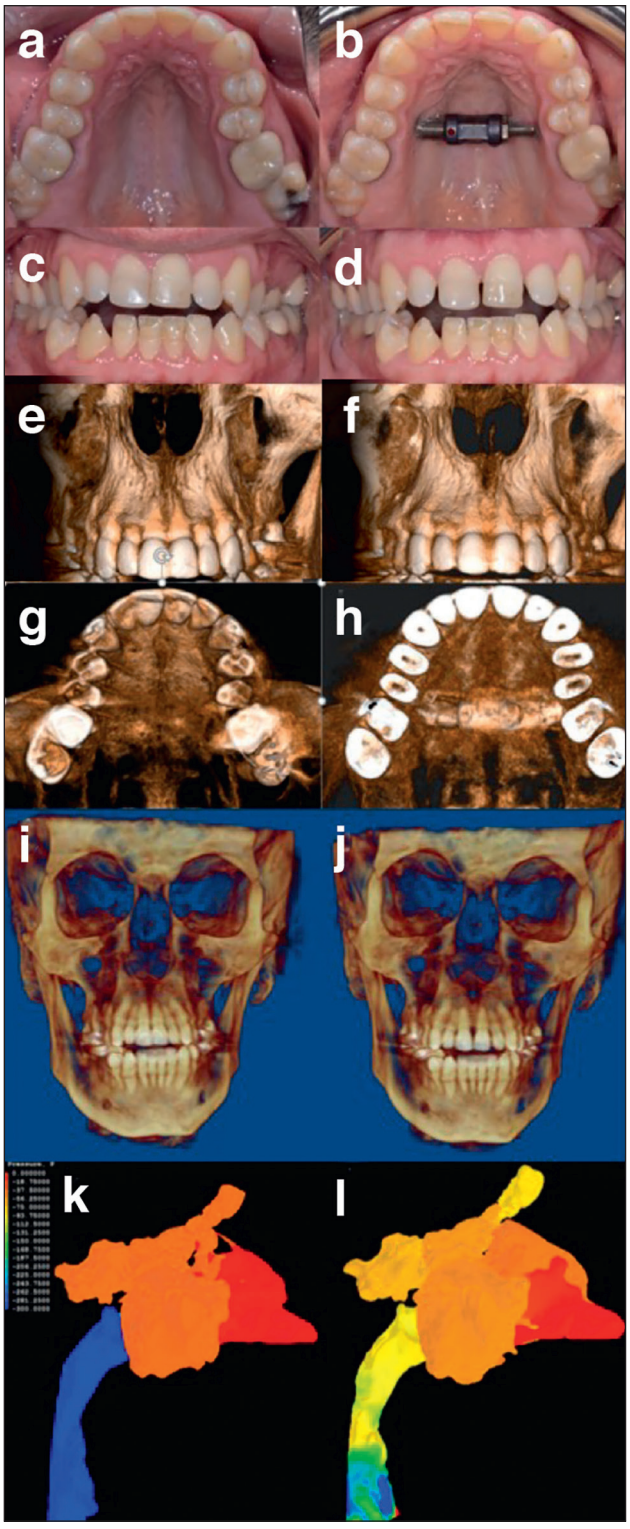

Figure 7

36-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) CFD showing preoperative airway pressures. (l) CFD showing postoperative airway pressures.

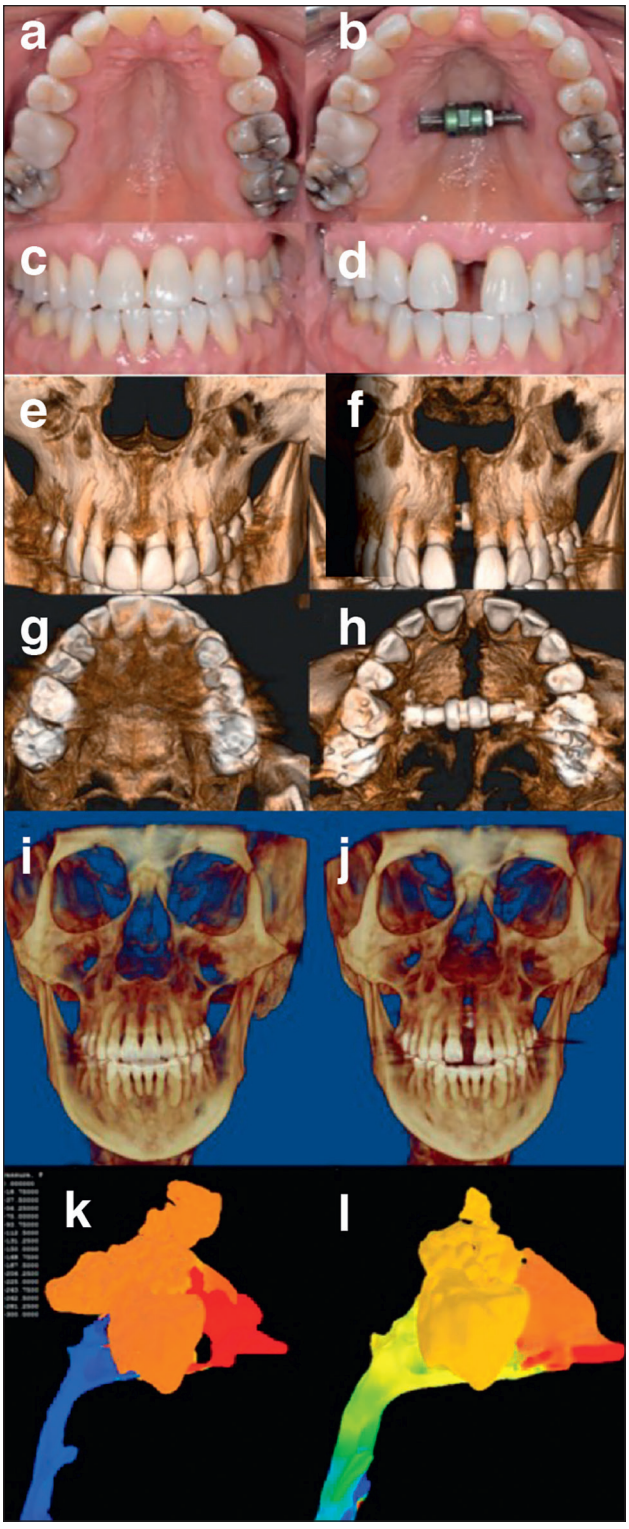

Figure 8

48-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) CFD showing preoperative airway pressures. (l) CFD showing postoperative airway pressures.

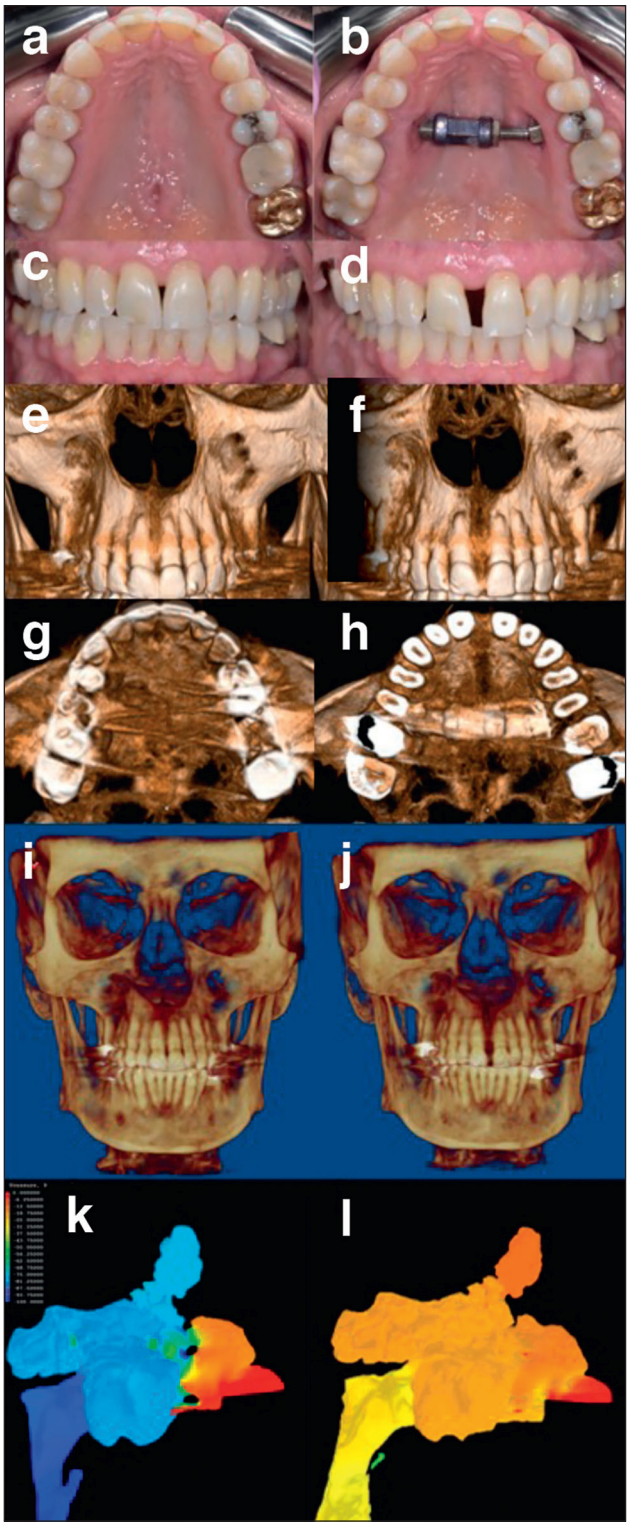

Figure 9

60-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) CFD showing preoperative airway pressures. (l) CFD showing postoperative airway pressures.

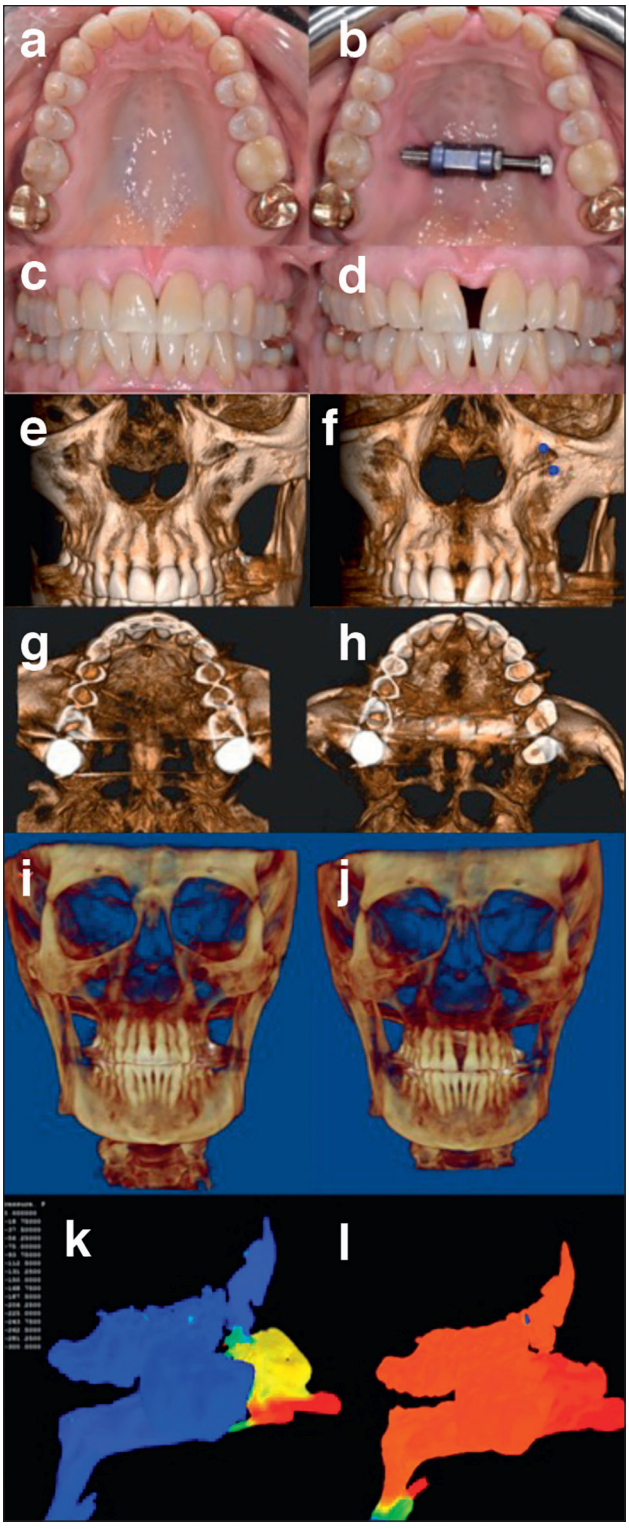

Figure 10

62-year-old patient's expansion photos, CBCT and CFD images. (a) Preoperative palatal view. (b) Postoperative palatal view showing the TPD in place at the completion of expansion. (c) Preoperative frontal view. (d) Postoperative frontal view. (e) Preoperative frontal view. (f) Postoperative frontal view at the completion of expansion showing widening at ANS. (g) Preoperative palatal view. (h) Postoperative palatal showing a parallel expansion at the mid-palatal suture from ANS to PNS. (i) Preoperative frontal skull view. (j) Postoperative frontal skull view showing the expanded maxilla. Note the widening between the roots of the central incisors with minimal to no teeth tipping, expanded nasal aperture and modulation of the sutures at the nasofrontal region. (k) CFD showing preoperative airway pressures. (l) CFD showing postoperative airway pressures.

Due to the increasing complications that we have observed with over-expansion from DOME, the EASE procedure was designed to maximize the nasal airway expansion while minimizing the undesired effects. EASE focuses on the entire nasomaxillary complex, including the posterior region of the maxilla, which has been shown to be the most resistant to expansion[7,30]. The minimal anterior surgical intervention also eliminates concerns of esthetic changes including nasal base widening and lip shortening[1,10,13]. The release of the pterygomaxillary suture and posterior midpalatal suture along with direct pressure applied at the palatal bone promoted the separation of the maxilla in the posterior aspect that propagated anteriorly while avoiding extensive surgical intervention in the anterior maxilla. The resultant parallel expansion pattern along the midpalatal suture was achieved consistently. Most importantly, the entire nasal cavity was enlarged with the expansion extended to the nasofrontal region as demonstrated by the widening of the zygoma width and the modulation of the sutures at the nasofrontal region (Figs. 5 to 10).

The ratio of dental expansion to skeletal expansion was 1.28:1 (4.1 mm:3.2 mm) at canine and 1.3:1 (4.7 mm:3.6 mm) at first molar. It is evident that the skeletal impact of EASE is considerably more efficient than other types of expansion methods, which is usually accepted as being approximately 3:1 even when MARPE is utilized in adolescent and young adults[6,17,20,23]. The skeletal impact of EASE is also considerably greater than SARPE, with a reported dental to skeletal expansion ratio of 2.1:1 (7.0 mm:3.3 mm) in a meta-analysis review[2]. The difference in nasal airway expansion is more profound where SARPE expansion is primarily located at the alveolar region.

Furthermore, the skeletal effect achieved by EASE is even more impressive considering the mean age of the study group (35.0 years), which is the oldest study sample of maxillary expansion published to date. The results also showed that a nearly pure skeletal nasomaxillary expansion with expansion pattern simulating the pediatric pattern that extends to the nasofrontal sutures is realistic in middle age and beyond.

This is the first description of nasomaxillary expansion at both the anterior nasal cavity (at the nasal vestibule and nasal valves) along with expansion of the posterior nasal cavity (at the junction of the nasal airway to the nasopharyngeal region). Traditionally, the molar region has been reported as the posterior extent of the maxillary expansion. However, the first molar only represents the midway of the nasal cavity. EASE resulted in expansion of the nasal airway posterior to the first molar, including the PNS. This expansion pattern is quite different than the typical fan shape surgical expansion where nasal floor widening can be inconsistent or inadequate[7,8,24]. The lack of posterior midpalatal suture opening minimally impacts the posterior nasal airway and the posterior hard palate, where several palatopharyngeal muscles originate, which impacts the nasopharyngeal and retropalatal airway. Despite the near consistent expansion pattern achieved by EASE, we did find the opening isn't completely parallel, with variation of the skeletal widening of the nasal sidewall at canine (3.2 mm), molar (3.6 mm), and PNS (2.2 mm). This is likely related to the direct pressure applied at the palatal shelves near molar roots causing greater

Table 1. Baseline Demographic Characteristics of the Full Sample and the Computational Fluid Dynamics (CFD) Sub-sample.

Characteristics	Mean ± SD or Count (%)	Mean ± SD or Count (%)
	Full Sample (n=100)	CFD Sample (n=20)
Age, years	35.0 ± 13.5	35.4 ± 14.6
Gender		
Male	67 (67.0 %)	15 (75.0 %)
Female	33 (33.0 %)	5 (25.0 %)
Body Mass Index (BMI)	23.5 ± 3.0	23.1 ± 2.7

Abbreviations: CFD = Computational Fluid Dynamics.

Table 2. Pre- and Post-operative Dental and Skeletal Expansion Outcomes.

Characteristics (n=100)	Preoperative Mean ± SD	Postoperative Mean ± SD	Difference (95% CI)	t (df=99)	p-value
Dental Expansion					
Intercanine width (mm)	24.36 ± 2.88	28.19 ± 2.98	3.83 (3.46 - 4.19)	20.77	<0.0001
Intermolar width (mm)	33.65 ± 3.07	38.42 ± 3.63	4.77 (4.44 - 5.10)	28.57	<0.0001
Skeletal Expansion					
Nasal anterior nasal spine width at canine (mm)	22.58 ± 2.20	25.70 ± 2.11	3.12 (2.90 - 3.34)	28.57	<0.0001
Nasal sidewall width at first molar (mm)	29.27 ± 2.88	32.91 ± 2.74	3.64 (3.43 - 3.84)	34.61	<0.0001
Nasal sidewall width at posterior nasal spine (mm)	29.20 ± 2.54	31.58 ± 2.58	2.39 (2.16 - 2.61)	21.05	<0.0001
Zygomatic width (mm)	108.74 ± 5.40	110.91 ± 5.82	2.17 (1.95 - 2.39)	19.88	<0.0001

Abbreviations: df = degrees of freedom, mm = millimeters.

alveolar bending/teeth tilting in the region as well as lesser resistance to expansion anteriorly and greater resistant to expansion posteriorly.

The impact of nasomaxillary expansion pattern achieved by EASE on airflow properties was modeled using CFD. CFD simulation showed a dynamic change following expansion in airway pressure and velocity not only in the nasal airway but also consistently affected the upper airway segments posterior to the nasal airway. We postulate that the reduction of nasal airway resistance from expansion led to lower airway velocity and reduced negative nasal pressure on inspiration, with subsequent impact on the rest of the airway. The effect rendered the compliant airway less collapsible to the negative intraluminal pressure on inspiration, thus leading to reduction of OSA severity[18]. A similar concept has previously been proposed in the CFD study in children with OSA[34]. The impact on airway negative pressure by EASE was shown to be greater than five times that of the DOME on CFD simulation[16].

The major limitations of this study is that it is retrospective in nature and lacks a control group. However, because the objective of the study was to assess the skeletal changes comparing CBCT and CDF of preoperative and postoperative imagings, we believe this study design lends sufficient credibility to the results. Additionally, retrospective study design in evaluating maxillary expansion results based on imaging or dental casts has been commonly used. Further studies are needed to show the clinical benefit of the EASE procedure evaluating obstructive sleep apnea outcomes in a larger sample size with longer follow-up periods. While a study comparing EASE patients with a control group of untreated patients plus traditional SARPE patients may have been ideal, it was not feasible because we have abandoned the SARPE approach completely.

5. Conclusion

EASE is a surgical approach to expand the nasomaxillary region extending from the nasal floor to the nasofrontal region. It results in a near parallel expansion of the midpalatal suture from the ANS to PNS with an almost pure skeletal movement of minimal dental effect. The expansion of the nasomaxillary complex results in reduction of airway pressure and velocity in simulated airway study by CFD, which is postulated to improve airway collapse in OSA.

Table 3. Pre- and Post-operative Mean Airflow Velocity and Negative Pressure Outcomes Based on Simulation of Airway Ventilation with Computational Fluid Dynamics (CFD).

Characteristics (n=20)	Preoperative Mean ± SD	Postoperative Mean ± SD	Difference Mean ± SD	V	p-value
Mean Airflow Velocity					
Nasal airway (m/s)	18.78 ± 15.90	7.61 ± 1.95	-11.17 ± 37.45	1	p=0.0001
Nasopharyngeal airway (m/s)	3.00 ± 3.14	2.17 ± 1.09	-0.84 ± 8.27	85	p=0.47
Oropharyngeal airway (m/s)	4.15 ± 2.94	3.16 ± 1.22	-0.99 ± 6.12	40.5	p=0.05
Hypopharyngeal airway (m/s)	3.88 ± 1.58	3.75 ± 1.74	-0.13 ± 4.78	95	p=0.72
Mean Negative Pressure					
Nasal airway (Pa)	-395.46 ± 720.95	-32.65 ± 19.19	362.82 ± 1712.442	208	<0.0001
Nasopharyngeal airway (Pa)	-394.18 ± 719.38	-33.60 ± 18.51	360.58 ± 1711.64	205	<0.0001
Oropharyngeal airway (Pa)	-405.86 ± 710.82	-39.40 ± 19.32	366.46 ± 1687.96	207	<0.0001
Hypopharyngeal airway (Pa)	-422.57 ± 704.86	-55.06 ± 33.68	367.51 ± 1651.66	208	<0.0001

Abbreviations: m/s = meter per second, Pa = pascal, CFD = Computational Fluid Dynamics.

Links of interest

The authors declare that they have no interest in the data published in this article.

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Original article

Should Mandibular Symphyseal Distraction Osteogenesis be considered in OSA Surgery?

Kasey LI[1*], Christian GUILLEMINAULT[2]

[1] Sleep Apnea Surgery Center, 1900 University Avenue, Suite 105, East Palo Alto, CA, USA
[2] Deceased. Professor (formerly). Sleep Medicine Division, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA

KEYWORDS:
Maxillomandibular expansion / Mandibular symphyseal distraction osteogenesis / MSDO / Sleep apnea / DOME / SARPE / EASE / Nasomaxillary expansion

ABSTRACT – Introduction: *Surgical maxillary expansion for the treatment of obstructive sleep apnea (OSA) has become common place. To maximize airway improvement, over-expansion of the maxilla can occur, resulting in an excessively widened maxilla that creates a mismatch to the mandible. Therefore, mandibular symphyseal distraction osteogenesis (MSDO) to widen the mandible along with maxillary expansion is being increasingly advocated in OSA surgery.* **Methods:** *The authors discuss their 20-year experience with MSDO and surgical maxillary expansion. They also analyze the airway impact between Distraction Osteogenesis Maxillary Expansion (DOME) and Endoscopically-Assisted Surgical Expansion (EASE) based on currently available computational fluid dynamic (CFD) data, which has implications in whether MSDO needs to be considered.* **Results and Conclusion:** *The goal of surgical maxillary expansion is to enlarge the nasal cavity and reduce the airway resistance. CFD data demonstrates that EASE results in a much greater reduction in airway resistance as compared to DOME. EASE achieved a 12-fold reduction in nasal airway resistance compared to 3-fold reduction by DOME; a 12-fold reduction of retropalatal airway resistance as compared to 3-fold reduction by DOME; a 10-fold reduction of oropharyngeal airway resistance as compared to a 3-fold reduction by DOME, and an 8-fold reduction of hypopharygeal airway resistance as compared to a 3-fold reduction by DOME. Because there is no physiologic basis or data that demonstrates mandibular widening improves OSA, an airway centric surgical expansion technique such as EASE can achieve a much greater airway impact without needing excessive maxillary widening, thus eliminating the necessity MSDO.*

* Correspondance : drli@sleepapneasurgery.com

1. Introduction

Since the first report of surgical maxillary expansion for the treatment of obstructive sleep apnea (OSA)[1], procedures such as Surgically Assisted Rapid Palatal Expansion (SARPE) and Distraction Osteogenesis Maxillary Expansion (DOME) have become common place[7]. Because the goal of maxillary expansion is to enlarge the nasal airway in OSA patients, over-widening of the maxilla (10+mm) in order to maximize airway expansion has been advocated[7]. However, an excessively widened maxilla can create a mismatch to the mandible, resulting in difficulty in coordinating the two arches orthodontically. Because of this, Mandibular Symphyseal Distraction Osteogenesis (MSDO) performed to widen the mandible, is being increasingly advocated along with maxillary expansion in OSA surgery.

Combining MSDO with SARPE for the treatment of OSA is nothing new. In fact, it is a 20-year-old concept[2,4]. The authors aim to examine whether combining MSDO and SARPE/DOME for the treatment of OSA is a rational approach.

2. Methods

The authors discuss their 20-year experience with MSDO and surgical maxillary expansion. The authors also compare the airway impact between DOME and Endoscopically-Assisted Surgical Expansion (EASE) based on currently available computational fluid dynamic (CFD) data, which has implications on whether MSDO needs to be considered.

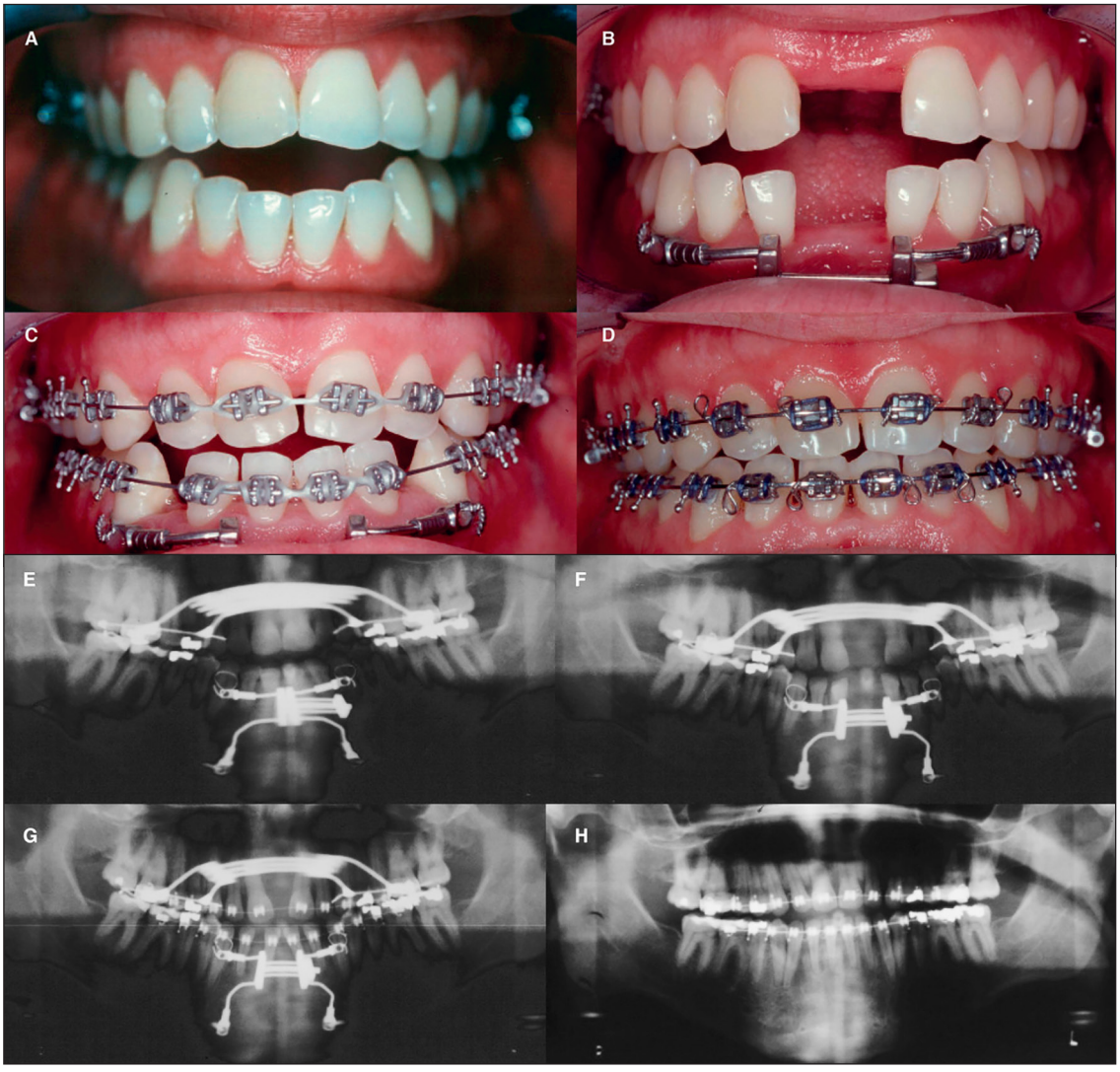

Figure 1
31-year-old man underwent SARPE/MSDO for OSA. (A-D) Clinical progression. (E-H) Radiographic progression.

3. Results and Discussion

The authors first published their experience in combining surgically assisted rapid palatal expansion (SARPE) and MSDO for the treatment of OSA in 2004 (Figs. 1 and 2)[2,4]. Since the initial publication, the authors have performed numerous combined, as well as isolated surgical maxillary expansions by SARPE and mandibular widening by MSDO for OSA. The rationale of the combined approach from 20 years ago is the same as what most practitioners believe today: that enlarging the oral cavity improves OSA, and larger the better.

However, our knowledge of OSA and the airway impact from different surgical maneuvers has evolved since 2004.

It must be emphasized that the goal of maxillary expansion is not to widen the oral cavity, but to widen the nasal cavity if the treatment objective is to improve OSA. Nasal expansion reduces nasal resistance which improves nasal breathing. The reduction of nasal airway resistance also lessens the retropalatal, oropharyngeal and hypopharyngeal airway collapse by reducing the negative airway pressure from improved nasal respiration[3,5]. To maximize the nasal expansion while avoiding the excessive maxillary widening as well as the need for mandibular widening, EASE was developed by the authors in 2017[6]. EASE is considerably less invasive but a much more efficient technique to expand the nasal cavity as compared to SARPE and DOME (see Fig. 3).

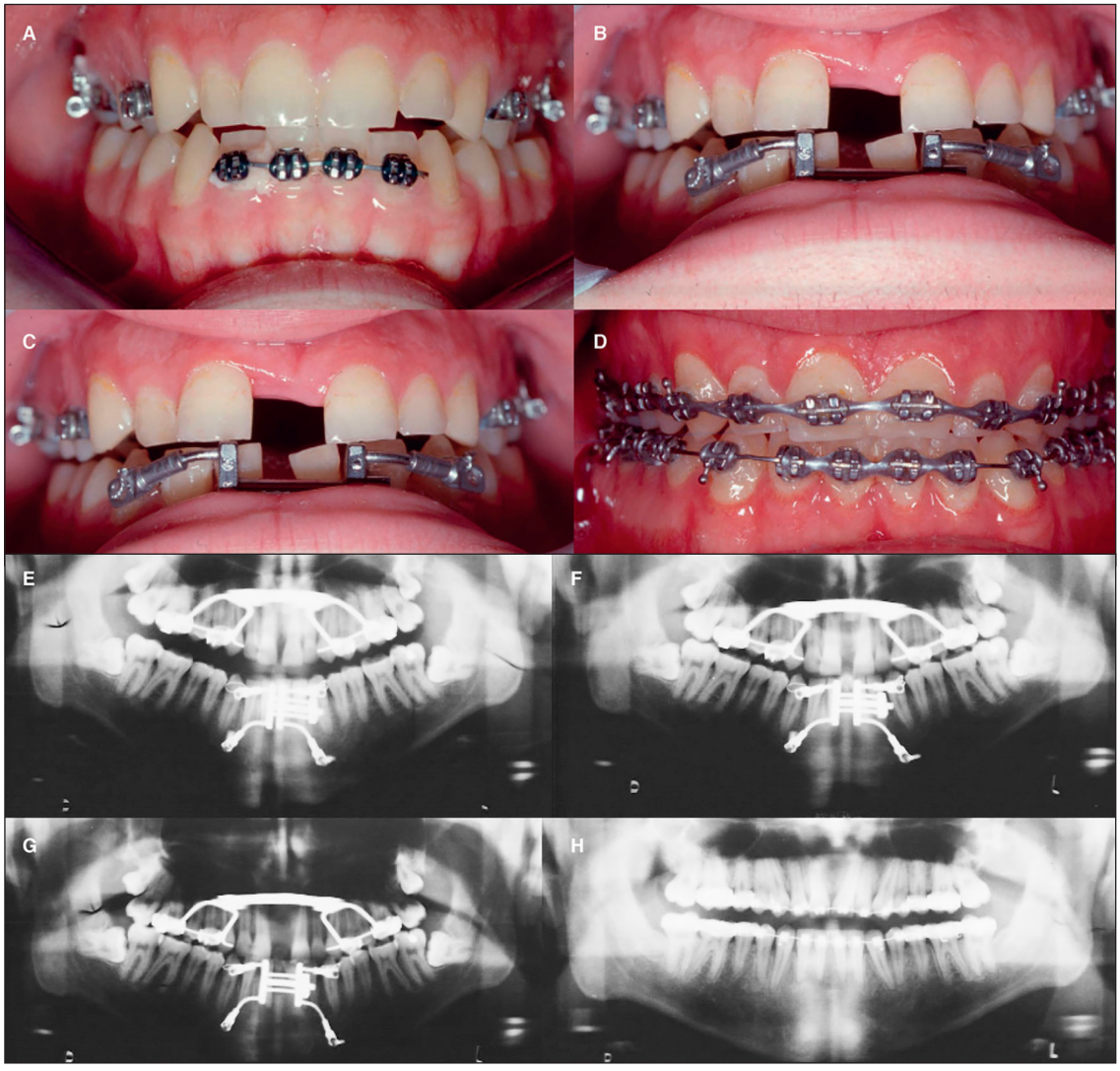

Figure 2
25-year-old man underwent SARPE/MSDO for OSA. (A-D) Clinical progression. (E-H) Radiographic progression.

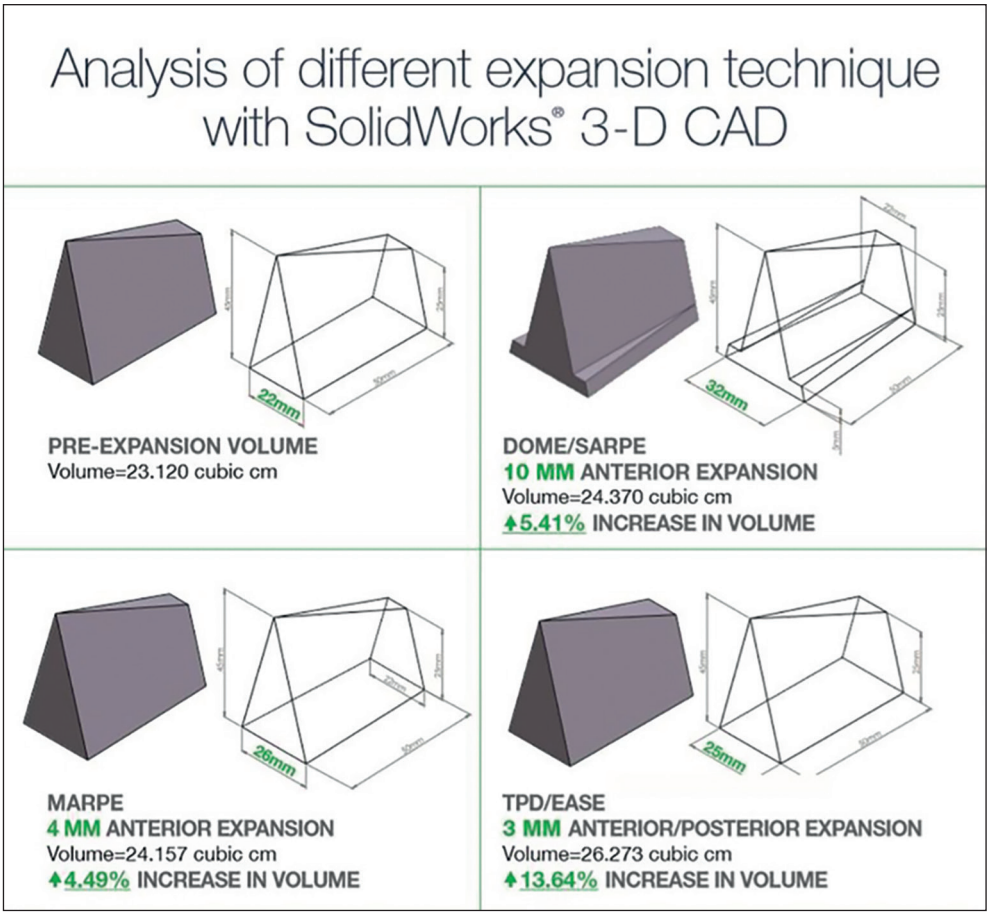

Figure 3

Solid modeling completer-aided design with SolidWorks® comparing expansion pattern and resulting nasal airway changes with different techniques.

Tableau 1. Computational Fluid Dynamics (CFD) Data.

AIRWAY SEGMENT	DOME Pre and Post pressure Mean ± SD Pa (n=20)	EASE Pre and Post pressure Mean ± SD Pa (n=20)
Nasal airway	-158.4 ± 115.3 to -48.6 ± 28.7	-395.5 ± 721.0 to -32.7 ± 19.2
Retropalatal airway	-174.8 ± 119.9 to -52.5 ± 31.3	-394.2 ± 719.4 to -33.6 ± 18.5
Oropharyngeal airway	-177.0 ± 118.4 to -54.9 ± 31.8	-405.9 ± 710.8 to -39.4 ± 19.3
Hypopharyngeal airway	-177.9 ± 117.9 to -56.9 ± 32.1	-422.6 ± 704.9 to -55.1 ± 33.7

The efficiency of EASE in impacting the airway resistance was demonstrated by current available computational fluid dynamic (CFD) data of EASE and DOME (Table 1)[3,5].

EASE achieved a 12-fold reduction in nasal airway resistance compared to 3-fold reduction by DOME; a 12-fold reduction of retropalatal airway resistance as compared to 3-fold reduction by DOME; a 10-fold reduction of oropharyngeal airway resistance as compared to a 3-fold reduction by DOME, and an 8-fold reduction of hypopharygeal airway resistance as compared to a 3-fold reduction by DOME. Moreover, EASE does not result in an excessively widened maxilla compared to DOME/SARPE, thus eliminating the need for mandibular widening.

4. Conclusions

The goal of surgical maxillary expansion is to enlarge the nasal cavity to reduce the airway resistance. Since there is no physiologic basis or data that demonstrates mandibular widening improves OSA, an airway centric surgical expansion technique such as EASE can achieve a much greater airway impact without needing excessive maxillary widening, thus eliminating the necessity MSDO.

Links of interest

The authors declare that they have no interest in the data published in this article.

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Original article

Maxillomandibular Advancement for OSA: A 25-year perspective

Kasey LI[1*], Jon-Erik HOLEY[2], Christian GUILLEMINAULT[3]

[1] Sleep Apnea Surgery Center, 1900 University Avenue, Suite 105, East Palo Alto, CA, USA
[2] Pulmonary and Critical Care, Stanford University School Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA
[3] Deceased. Sleep Medicine Division, Stanford University School of Medicine, Stanford, 3165 Porter Dr, Palo Alto, CA 94304, USA

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ABSTRACT – Objective: *The aim of this study was to evaluate the result of maxillomandibular advancement (MMA) for the treatment of obstructive sleep apnea (OSA) by a single surgeon.* **Materials and Methods:** *Patients that underwent MMA for the treatment of OSA over a 25-year period were included in the study. Patients who initially presented for revision MMA surgery were excluded. Demographics (e.g., age, gender, pre- and post-MMA body mass index [BMI]), pre- and post-MMA cephalometrics (e.g., sella-nasion-point A angle [SNA], sella-nasion-point B angle [SNB], posterior airway space base of tongue [PAS]) and pre- and post-MMA sleep study metrics (e.g., respiratory disturbance index [RDI], lowest desaturation [SpO_2-nadir], oxygen desaturation index [ODI], total sleep time [TST], % TST Stage N3 sleep, % TST rapid eye movement [REM] sleep) were abstracted. MMA surgical success was defined as a ≥ 50% reduction in RDI (or ODI) and post-MMA RDI (or ODI) < 20 events/hour. MMA surgical cure was defined as a post-MMA RDI (or ODI) < 5 events/hour.* **Results:** *A total of 1010 patients underwent MMA for the treatment of OSA. The mean age was 39.6 ± 14.3 years, and the majority were male (77%). Nine hundred forty-one patients with complete pre- and postoperative PSG data were analyzed. The mean ODI and RDI improved from 32.6 ± 27.4 to 7.7 ± 15.5 and 39.1 ± 24.2 to 13.6 ± 14.6 events per hour, respectively. The overall surgical success and surgical cure based on ODI was 79.4% and 71.9%, respectively. The overall surgical success and surgical cure based on RDI was 73.1% and 20.7%, respectively. Stratified by preoperative RDI showed older age, greater BMI were associated with greater preoperative RDI. Bivariate predictors of greater RDI reduction include younger age, female gender, lower preoperative BMI, higher preoperative RDI, greater BMI reduction postoperatively and greater change in SNA and PAS. Bivariate predictors of surgical cure based on RDI (RDI < 5) include younger age, female gender, lower preoperative RDI, and greater change in SNA and PAS. Bivariate predictor of RDI success (RDI < 20) include younger age, female gender, lower preoperative BMI, lower preoperative RDI, greater BMI reduction, greater increase in SNA, SNB and PAS postoperatively. Comparison of the first 500 patients and the later 510 patients demonstrate patients undergoing MMA have become younger, having lower RDI while achieving a better surgical outcome. Linear multivariate associations of greater percentage RDI reduction include younger age, greater percent change of SNA, greater preoperative SNA, lower preoperative BMI and higher preoperative RDI.* **Conclusions:** *MMA is an effective treatment to improve OSA, but the result can vary. Patient selection based on favorable prognostic factors and maximizing the advancement distance can improve outcomes.*

* Correspondance : drli@sleepapneasurgery.com

1. Introduction

Maxillomandibular advancement (MMA) has become a well-accepted treatment of obstructive sleep apnea (OSA) since the early reports over 40 years ago[3,10,30]. However, despite numerous published case series on MMA results, prognostic factors are not well-established due to limited sample size. To improve the understanding of the impact of MMA on OSA, meta-analyses of pooled MMA data have been conducted. Patients with younger age and weight, lower apnea hypopnea index (AHI), and a greater degree of maxillary advancement were predictive of increased surgical success based on analysis of 320 subjects[8]. In a follow-up analysis of 518 subjects, preoperative AHI of fewer than 60 events per hour was shown to be the factor most strongly associated with surgical cure (AHI < 5)[31]. The rates of surgical success (AHI < 20) and cure (AHI < 5) were 389 (85.5%) and 175 (38.5%), respectively, among 455 patients with AHI data[31]. However, among the 68 patients with respiratory disturbance index (RDI) data, the impact on OSA was less dramatic. The rate of success and cure were 44 (64.7%) and 13 (19.1%), respectively.

Over the past 25 years, the authors have extensively studied the relationship between the airway and the maxillofacial skeleton. The principles of maximizing skeletal advancement, maintaining proper facial balance and occlusion while minimizing complications have been established[11-29]. This study was undertaken to assess the outcome of MMA for the treatment of OSA by a single surgeon (KKL).

2. Materials and Methods

Patients undergoing MMA for the treatment of OSA performed by a single surgeon (KKL) between 1997 and 2021 were retrospectively analyzed from prospectively collected clinical data. Patients with previous MMA that presented for revision surgery were excluded. The study was approved by the Stanford University review board (protocol ID # 15494) and was in accordance of the Declaration of Helsinki.

2.1. OSA Assessments

All patients underwent in-lab type-1 monitored polysomnography evaluations pre- and post-MMA that were performed per American Academy of Sleep Medicine's guidelines[1]. The respiratory-disturbance index (RDI) was calculated as the number of apneas (≥ 90% reduction in thermistor flow for ≥ 10 seconds) plus hypopneas (≥ 30% reduction in nasal pressure amplitude accompanied by either a ≥ 3% pulse oximeter (SpO_2) reduction or electroencephalogram (EEG) arousal for ≥ 10 seconds) per hour of sleep. The oxygen desaturation index (ODI) was calculated as the number of ≥ 3% SpO_2 reductions from baseline per hour of sleep. Sleep apnea severity was defined as mild (5-14.9 events/hour), moderate (15-29.9 events/hour) or severe (≥ 30 events/hour).

2.2. Medical Record and Data Abstraction

Demographics (e.g., age, gender, pre- and post-MMA body mass index [BMI]), pre- and post-MMA cephalometrics (e.g., sella-nasion-point A angle [SNA], sella-nasion-point B angle [SNB], posterior airway space base of tongue [PAS]) and pre- and post-MMA sleep study metrics (e.g., RDI, SpO_2-nadir, ODI, total sleep time [TST], %TST Stage N3 sleep, %TST rapid eye movement [REM] sleep) were abstracted. MMA surgical success was defined as a ≥ 50% reduction in RDI (or ODI) and post-MMA RDI (or ODI) < 20 events/hour. MMA surgical cure was defined as a post-MMA RDI (or ODI) < 5 events/hour.

2.3. Analyses

All univariate and multivariate analyses were performed using Statistical Package for the Social Sciences version 22 for Windows (SPSS, Chicago, IL, USA). We compared categorical variables using a Fisher's exact test and continuous variables with a 2-tailed t-test (or a one-way analysis of variance [ANOVA] test as appropriate). The normality assumption for the ANOVA was assessed via the Kolmogorov-Smirnov test and a nonparametric test used for p-value calculations. Values are reported as mean ± standard deviation. A multivariate linear regression (dependent variable % reduction in RDI) was used to estimate the associations between baseline demographics, cephalometrics, and sleep study metrics, as well as changes in cephalometrics post-MMA, in relationship to improvements in sleep apnea metrics. We assessed each variable by stepwise backwards regression using a p-value cutoff ≤ 0.1. To ensure uniformity between covariate scaling, z-scores of these variables were generated (each variable divided by its standard deviation) resulting in all regression beta values having scaled

Table 1. Pre and Post-MMA Characteristics*.

	Pre-MMA	Post-MMA	P-value
Characteristics			
Age (n=1010)	39.6 ± 14.3	NA	NA
Male Gender (%) (n=1010)	77.0%	NA	NA
BMI (kg/m^2)¶ (n=908)	27.7 ± 4.3	27.5 ± 4.3	<0.001
Polysomography			
RDI (events/hour) (n=941)	39.1 ± 24.2	13.6 ± 14.6	<0.001
RDI ≥ 30/hr (%) (n=941)	54.8%	8.5%	<0.001
RDI ≥ 20/hr (%) (n=941)	77.1%	17.2%	<0.001
SpO_2 Nadir (%)‡ (n=922)	83.4 ± 10.1%	88.9 ± 6.4%	<0.001
ODI (desaturations/hour) (n=306)	32.6 ± 27.4	7.7 ± 15.5	<0.001
ODI ≥ 30/hr (%) (n=306)	47.7%	8.5%	<0.001
ODI ≥ 20/hr (%) (n=306)	55.9%	11.1%	<0.001
Sleep Stages†	55.9%	11.1%	<0.001
Total Sleep Time (min) (n=306)	363.9 ± 68.2	378.8 ± 67.5	0.002
REM Sleep (%) (n=306)	10.6 ± 5.3%	16.9 ± 6.4%	<0.001
Stage N3 Sleep (%) (n=306)	3.4 ± 5.3%	7.6 ± 7.7%	<0.001
Cephalometrics			
SNA (degrees) (n=305)	80.1 ± 3.1	81.5 ± 3.2	<0.001
SNB (degrees) (n=305)	77.1 ± 3.8	78.4 ± 3.3	<0.001
PAS (mm) (n=305)	5.4 ± 2.2	8.4 ± 2.5	<0.001
MP-H (mm) (n=305)	25.0 ± 7.1	22.1 ± 7.0	<0.001
PNS-P (mm) (n= 305)	45.1 ± 4.9	30.9 ± 3.7	<0.001
RDI Surgical Cure (%)# (n=941)	NA	20.7%	NA
ODI Surgical Cure (%)# (n=306)	NA	71.9%	NA
RDI Surgical Success (%)# (n=941)	NA	73.1%	NA
ODI Surgical Success (%)# (n=306)	NA	79.4%	NA

** Plus-minus values are mean (or percent) ± standard deviation. Values in parenthesis are the number of patients evaluated. Abbreviations: BMI (body mass index), MMA (maxillomandibular advancement), ODI (oxygen desaturation index), PAS (posterior airway space – base of tongue), PNS-P (distance of posterior nasal spine to the tip of the soft palate), RDI (respiratory disturbance index), REM (rapid eye movement), SNA (sella-nasion-Point A angle), SNB (sella-nasion-Point B angle), SpO_2 (pulse oxyhemoglobin saturation). † Reported as a percent of total sleep time. ‡ The SpO_2 nadir is the lowest oxyhemoglobin saturation measured during sleep. Only patients with both pre and post-MMA SpO_2 nadir are included. # Surgical cure defined an RDI (or ODI) < 5 events/hour post-MMA. Surgical success defined as the percent of subjects with an RDI (or ODI) < 20/hour and a ≥ 50% reduction in the RDI (or ODI) post-MMA. ¶ Only patients with both pre and post-MMA BMI are included.*

standardized units of the independent predictors. A two-tailed p-value <0.05 was considered statistically significant.

3. Results

A total of 1010 patients underwent MMA for the treatment of OSA. The mean age was 39.6 ± 14.3 years, and the majority were male (77%). Nine hundred forty-one patients with complete pre- and postoperative PSG data were analyzed. The mean ODI and RDI improved from 32.6 ± 27.4 to 7.7 ± 15.5 and 39.1 ± 24.2 to 13.6 ± 14.6 events per hour, respectively. The overall surgical success and surgical cure based on ODI was 79.4% and 71.9%, respectively. The overall surgical success and surgical cure based on RDI was 73.1% and 20.7%, respectively (Table 1).

Stratified by preoperative RDI showed older age, greater BMI were associated with greater preoperative RDI (Table 2). Bivariate predictors of greater RDI reduction include younger age, female gender, lower preoperative BMI, higher preoperative RDI, greater BMI reduction postoperatively and greater change in SNA and PAS (Table 3). Bivariate predictors of surgical cure based on RDI (RDI < 5) include younger age, female gender, lower preoperative RDI, and greater change in SNA and PAS (Table 4). Bivariate predictor of RDI success (RDI < 20 include younger age, female gender, lower preoperative BMI, lower preoperative RDI, greater BMI reduction, greater increase in SNA, SNB and PAS postoperatively (Table 5). Comparison of the first 500 patients and the later 510 patients demonstrate patients undergoing MMA have become younger, having lower RDI while achieving a better surgical outcome (Table 6).

Linear multivariate associations of greater percentage RDI reduction include younger age, greater percent change of SNA, greater preoperative SNA, lower preoperative BMI and higher preoperative RDI (Fig. 1).

4. Discussion

The results of this study demonstrate that patients with younger age, lower BMI, lower RDI and female gender achieve a better surgical outcome as measured by PSG parameters. Furthermore, a larger advancement distance (percentage increase of SNA and SNB) and a greater impact on airway size (larger increase in PAS) resulted in a greater reduction in RDI in achieving surgical success.

The application of MMA in treating OSA has evolved over the past 25 years[11-29]. MMA has changed from a last stage operation of the phased surgical protocol to a primary, single stage treat-

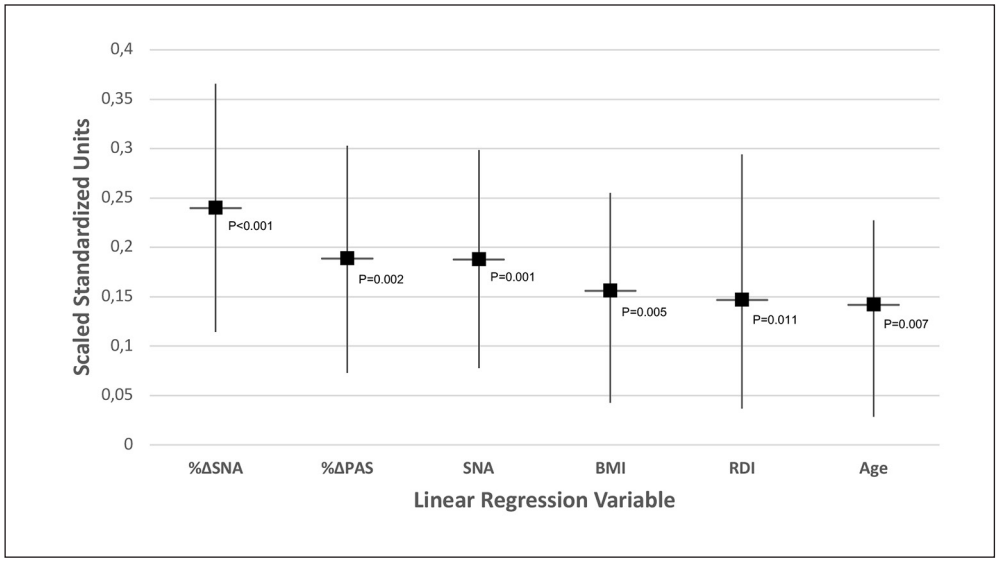

Figure 1

Multivariate Associations with Percent RDI Reduction Post MMA. Linear regression model with percent reduction in RDI (continuous variable) as dependent variable. All regression beta values are scaled standardized units of the independent predictors. Regression beta point estimate with 95% confidence intervals shown for each included variable. Initial model variables included age, pre-MMA BMI, male gender, pre-MMA RDI, pre-MMA SNA, pre-MMA SNB, pre-MMA PAS, post-MMA BMI percent change, post-MMA percent change SNA, post-MMA percent change SNB, and post-MMA percent change PAS. Final model developed utilizing backwards elimination (p-value < 0.10 cutoff). Predictors of increased percent RDI reduction post MMA in final model include greater positive percent change in SNA ($\beta = 0.240$, $p < 0.001$), greater positive percent change in PAS ($\beta = 0.189$, $p = 0.002$), greater pre-MMA SNA angle ($\beta = 0.188$, $p = 0.001$), lower pre-MMA BMI ($\beta = 0.154$, $p = 0.005$), greater pre-MMA RDI ($\beta = 0.147$, $p = 0.011$), and younger age ($\beta = 0.142$, $p = 0.007$). Model R2 is 0.201 (adjusted for number of predictors). Including various interaction terms (age*RDI, BMI*RDI, Male*RDI, SNA*RDI, SNB*RDI, PAS*RDI, Male*BMI, Age*Male) and/or polynomial variables (age2, BMI2, RDI2, RDI3) did not improve data fit and were not included in final model. Abbreviations: BMI (body mass index), MMA (maxillomandibular advancement), PAS (posterior airway space –base of tongue), RDI (respiratory disturbance index), SNA (sella-nasion-Point A angle), SNB (sella-nasion-Point B angle), %ΔPAS (percent PAS reduction), and %ΔSNA (percent SNA reduction).

Table 2. Patient Characteristics Stratified by Pre-MMA RDI*.

Characteristics	Pre-MMA RDI			P-value†
	< 30/hour (n=425)	30-59.9/hour (n=338)	≥ 60/hour (n=178)	
Pre-MMA				
Age (years)	33.7 ± 13.9 (425)	44.5 ± 12.3 (338)	45.7 ± 12.2 (178)	**<0.001**
Male (%)	69.9% (425)	81.4% (338)	91.6% (178)	**<0.001**
BMI (kg/m^2)	26.0 ± 2.5 (412)	27.8 ± 4.1 (338)	31.4 ± 5.6 (175)	**<0.001**
BMI > 30 kg/m^2 (%)	5.9% (412)	20.1% (338)	52.2% (175)	**<0.001**
Cephalometrics				
SNA (degrees)	80.2 ± 2.7 (60)	80.6 ± 3.2 (117)	79.8 ± 3.2 (136)	0.118
SNB (degrees)	77.3 ± 3.6 (60)	77.3 ± 3.9 (117)	76.9 ± 3.8 (135)	0.765
PAS (mm)	6.3 ± 2.4 (60)	5.5 ± 2.2 (111)	4.9 ± 2.0 (135)	0.602
Polysomnography				
RDI (events/hour)	19.2 ± 5.9 (425)	42.7 ± 9.0 (338)	79.7 ± 15.8 (178)	**<0.001**
SpO_2 Nadir (%)	88.9 ± 5.4% (421)	82.9 ± 8.2 (331)	71.4 ± 10.9 (177)	**<0.001**
ODI (desaturations/hour)	7.4 ± 6.9 (60)	19.9 ± 14.9 (111)	54.3 ± 24.7 (135)	**<0.001**
REM Sleep (% TST)	13.5 ± 5.6% (60)	11.1 ± 4.5% (111)	8.8 ± 5.2 (135)	**0.003**
Stage III/IV Sleep (% TST)	6.8 ± 7.4% (60)	3.4 ± 4.6% (111)	1.8 ± 3.7% (135)	**0.002**
Post-MMA				
BMI (kg/m^2)	25.9 ± 2.6 (379)	27.7 ± 4.2 (308)	31.4 ± 5.6 (172)	**<0.001**
Percent Change in BMI (%)	-0.7 ± 1.3% (378)	-0.7 ± 1.2% (303)	-0.5 ± 3.5% (172)	0.443
Cephalometrics				
SNA (degrees)	80.6 ± 2.9 (59)	81.7 ± 2.9 (111)	81.8 ± 3.5 (135)	0.039
Change in SNA (degrees)	0.004 ± 0.02 (59)	0.01 ± 0.02 (111)	0.02 ± 0.03 (135)	**<0.001**
SNB (degrees)	77.5 ± 0.03 (59)	78.5 ± 0.03 (111)	78.7 ± 0.03 (135)	0.055
Change in SNB (degrees)	0.003 ± 0.01 (59)	0.01 ± 0.02 (111)	0.02 ± 0.02 (135)	**<0.001**
PAS (mm)	8.2 ± 2.6 (59)	8.5 ± 2.3 (111)	8.5 ± 2.6 (135)	0.639
Change in PAS (mm)	1.9 ± 2.2 (59)	3.0 ± 2.1 (111)	3.7 ± 2.4 (135)	**<0.001**
Polysomnography				
RDI (events/hour)	8.2 ± 6.1 (425)	15.2 ± 11.7 (338)	23.2 ± 24.9 (178)	**<0.001**
Percent Change in RDI (%)	-56.0 ± 35.3% (425)	-63.8 ± 27.6% (338)	-70.0 ± 32.1% (178)	**<0.001**
RDI 5-14.9/hour (%)	58.6% (425)	47.3% (338)	36.0% (178)	**<0.001**
RDI 15-29.9/hour (%)	11.5% (425)	29.3% (338)	25.3% (178)	**<0.001**
RDI ≥ 30/hour (%)	0.1% (425)	4.0% (338)	4.4% (338)	**<0.001**
SpO_2 Nadir (%)	91.8 ± 3.9% (418)	88.5 ± 4.5% (332)	83.3 ± 9.3% (177)	**<0.001**
Percent Change in SpO_2 Nadir (%)	3.5 ± 5.5% (417)	7.6 ± 10.9% (328)	18.5 ± 17.5% (177)	**<0.001**
REM Sleep (% TST)	17.1 ± 6.1% (60)	16.2 ± 6.2% (111)	17.1 ± 6.7 (135)	0.829
Percent Change in REM Sleep (%)	70.7 ± 216.3% (60)	81.9 ± 187.5% (111)	207.8 ± 346.6% (135)	0.558
Stage III/IV Sleep (% TST)	10.9 ± 8.6% (60)	6.6 ± 6.2% (111)	6.9 ± 8.0% (135)	**0.002**
Percent Change in Stage III/IV (%)	221.8 ± 495.7% (60)	235.7 ± 473.1% (111)	335.7 ± 567.3 (135)	**0.868**
ODI (desaturations/hour)	2.2 ± 4.5 (60)	5.2 ± 9.5 (111)	12.1 ± 20.7 (135)	**<0.001**
RDI Surgical Cure (%)‡	29.6% (425)	12.1% (338)	15.7% (178)	**<0.001**
ODI Surgical Cure (%)	86.7% (60)	73.9% (111)	63.7% (135)	**0.004**
RDI Surgical Success (%)‡	73.2% (425)	74.0% (338)	66.3% (178)	0.148
ODI Surgical Success (%)	85.0% (60)	82.9% (111)	80.7% (135)	0.759

** Mean (or percent) ± standard deviation. The number of patients is shown in parentheses. Abbreviations: BMI (body mass index), MMA (maxillomandibular advancement), ODI (oxygen desaturation index), PAS (posterior airway space – base of tongue), REM (rapid eye movement), RDI (respiratory disturbance index), SNA (sella-nasion-Point A angle), SNB (sella-nasion-Point B angle), SpO_2 (pulse oxyhemoglobin saturation). † P-value assesses whether mean differences between the groups are statistically significant. ‡ Surgical cure defined an RDI (or ODI) < 5 events/hour post-MMA. Surgical success defined as the percent of subjects with an RDI (or ODI) < 20/hour and a ≥ 50% reduction in the RDI (or ODI) post-MMA.*

Table 3. Patient Characteristics Stratified by Percent Reduction in RDI Post-MMA*.

Characteristics	Percent RDI Reduction				P-value†	P-value‡
	≥ 75.0% (n=367; 39.0%)	50-74.9% (n=362; 38.5%)	25-49.9% (n=120; 12.8%)	< 24.9% (n=92; 9.8%)		
Pre-MMA						
Age (years)	38.8 ± 14.3 (367)	38.4 ± 14.4 (362)	41.9 ± 14.4 (120)	46.8 ± 10.0 (92)	**<0.001**||	**<0.001**
Age > 50 years (%)	24.8% (367)	25.7% (269)	33.3% (120)	42.4% (92)	**0.003**	**0.001**
Male (%)	80.4% (367)	72.1% (362)	80.0% (120)	90.2% (92)	**0.001**	**0.031**
BMI (kg/m^2)	28.3 ± 4.8 (363)	26.4 ± 3.0 (343)	27.9 ± 3.8 (116)	30.0 ± 5.4 (91)	**0.048**||	**0.030**
BMI > 30 kg/m^2 (%)	24.5% (363)	9.3% (343)	24.1% (116)	40.7% (91)	**<0.001**	**0.002**
Cephalometrics						
SNA (degrees)	80.0 ± 3.1 (164)	80.3 ± 2.8 (75)	80.9 ± 3.2 (26)	80.0 ± 3.5 (48)	0.696#	1.000
SNA < 80 degrees (%)	41.5% (164)	30.7% (75)	34.6% (26)	41.7% (48)	0.404	0.554
SNB (degrees)	76.8 ± 4.0 (164)	77.4 ± 3.7 (74)	77.4 ± 3.7 (22)	77.4 ± 3.7 (46)	0.219#	0.818
SNB < 80 degrees (%)	72.6% (164)	74.3% (74)	81.8% (22)	76.1% (46)	0.805	0.392
PAS (mm)	5.1 ± 2.2 (164)	5.8 ± 2.1 (74)	5.4 ± 2.0 (22)	5.7 ± 2.4 (46)	0.076#	0.354
Polysomnography						
RDI (events/hour)	47.6 ± 27.3 (367)	32.0 ± 17.7 (362)	33.8 ± 22.8 (120)	39.8 ± 25.0 (92)	**<0.001**||	**0.049**
SpO_2 Nadir (%)	81.3 ± 10.6% (362)	85.9 ± 8.1% (357)	86.0 ± 7.7% (120)	78.4 ± 13.1% (90)	0.521||	0.214
ODI (desaturations/hour)	36.1 ± 28.3 (164)	23.6 ± 20.4 (74)	31.5 ± 32.1 (22)	35.2 ± 29.1 (46)	0.484||	0.998
Post-MMA						
BMI (kg/m^2)	28.2 ± 4.9 (346)	26.3 ± 3.1 (320)	28.0 ± 3.9 (104)	30.0 ± 5.5 (89)	**0.027**||	**0.026**
Percent Change in BMI (%)	-0.8 ± 1.9 (345)	-0.7 ± 1.2 (315)	-0.6 ± 1.1 (104)	-0.1 ± 3.7 (89)	**0.005**#	**0.008**
Cephalometrics						
SNA (degrees)	82.3 ± 3.0 (163)	80.9 ± 2.9 (74)	80.8 ± 3.0 (22)	80.1 ± 3.5 (46)	**<0.001**#||	**<0.001**
SNA < 80 degrees (%)	17.8% (163)	21.6% (74)	36.4% (22)	41.3% (46)	**0.004**	**0.001**
Percent Change in SNA (%)	3.0 ± 3.8% (163)	0.9 ± 2.2% (74)	0.2 ± 1.1% (22)	0.2 ± 1.2% (46)	**<0.001**||	**<0.001**
SNB (degrees)	78.8 ± 3.2 (163)	78.1 ± 3.1 (74)	78.1 ± 3.3 (22)	77.5 ± 3.8 (46)	**0.016**#	**0.103**
SNB < 80 degrees (%)	57.7% (163)	68.9% (74)	81.8% (22)	76.1% (46)	**0.023**	**0.016**
Percent Change in SNB (%)	2.7 ± 3.6% (163)	1.0 ± 2.7% (74)	0.2 ± 1.1% (22)	0.2 ± 1.2% (46)	**<0.001**||	**<0.001**
PAS (mm)	9.1 ± 2.2 (163)	8.4 ± 2.4 (74)	7.0 ± 2.6 (22)	6.8 ± 2.6 (46)	**<0.001**#||	**<0.001**
Percent Change in PAS (%)	114.4 ±109.9% (163)	59.8 ± 62.8% (74)	32.9 ± 33.2% (22)	28.8 ± 53.6 (46)	**<0.001**||	**<0.001**
Change in PAS (mm)	4.1 ± 2.2 (163)	2.6 ± 2.0 (74)	1.6 ± 1.6 (22)	1.1 ± 1.9 (46)	**<0.001**#||	**<0.001**
Polysomnography						
RDI (events/hour)	6.2 ± 4.5 (367)	11.6 ± 6.6 (362)	20.8 ± 14.6 (120)	41.4 ± 24.2 (92)	**<0.001**||	**<0.001**
Percent Change in RDI (%)	-86.0 ± 7.0% (367)	-63.0 ± 7.1% (362)	-38.6 ± 7.0% (120)	12.8 ± 42.2% (92)	**<0.001**||	**<0.001**
SpO_2 Nadir (%)	89.8 ± 3.9% (360)	90.4 ± 4.8% (358)	88.3 ± 6.4% (119)	80.9 ± 11.8% (90)	**<0.001**||	**<0.001**
ODI (desaturations/hour)	1.4 ± 2.3 (164)	5.3 ± 9.2 (74)	16.7 ± 17.7 (22)	29.5 ± 25.6 (46)	**<0.001**||	**<0.001**
RDI Surgical Cure (%)§	45.5% (367)	7.7% (334)	0.0% (120)	0.0% (92)	**<0.001**	**<0.001**
ODI Surgical Cure (%)	92.7% (164)	73.0% (74)	22.7% (22)	19.6% (46)	**<0.001**	**<0.001**
RDI Surgical Success (%)§	98.6% (367)	90.1% (362)	0.0% (120)	0.0% (92)	**<0.001**	**<0.001**
ODI Surgical Success (%)	97.0% (164)	89.2% (66)	50.0% (22)	34.8% (46)	**<0.001**	**<0.001**

** Mean (or percent) ± standard deviation. The number of patients analyzed is shown in parentheses. Abbreviations: BMI (body mass index), MMA (maxillomandibular advancement), ODI (oxygen desaturation index), PAS (posterior airway space – base of tongue), RDI (respiratory disturbance index), SNA (sella-nasion-Point A angle), SNB (sella-nasion-Point B angle), SpO_2 (pulse oxyhemoglobin saturation). † P-value assesses whether differences between the groups are statistically significant (Weighted linear trend for continuous data; Fisher's exact 2-sided p-value used for categorical data). ‡ P-value assesses whether difference between ≥ 75% vs < 24.9% groups are statistically significant (Tukey [Levene's p > 0.05] or Games-Howell test for linear; Fisher's exact 2-sided for categorical data). §Surgical cure defined as an RDI (or ODI) < 5 events/hr post-MMA. Surgical success defined as the percent of subjects with an RDI (or ODI) <20/hour and a ≥50% reduction in the RDI (or ODI) post-MMA. # Levene's test was not statistically significant (p > 0.05) for the one-way ANOVA comparison, suggesting the variances are homogenous. || Welch's ANOVA p-value < 0.05.*

Table 4. Predictors of Post-MMA OSA Surgical Cure*.

Predictor	Post MMA			Post MMA		
	Cure (RDI < 5) (n=195; 20.7%)	No Cure (RDI ≥ 5) (n=746; 79.3%)	P-value‡	Cure (ODI < 5) (n=220; 71.9%)	No Cure (ODI ≥ 5) (n=86; 28.1%)	P-value‡
Pre-MMA						
Age (years)	32.6 ± 13.8 (195)	41.8 ± 13.7 (746)	**<0.001**	45.8 ± 11.7 (220)	51.3 ± 10.9 (86)	**<0.001**
Age > 50 years (%)	11.8% (195)	32.2% (746)	**<0.001**	37.7% (220)	58.1% (86)	**0.001**
Male (%)	70.8% (195)	80.0% (746)	**<0.001**	92.7% (220)	98.8% (86)	**0.048**
BMI (kg/m^2)	27.1 ± 4.6 (193)	27.9 ± 4.2 (720)	0.051	29.8 ± 5.7 (220)	32.5 ± 5.5 (86)	**<0.001**
BMI > 30 kg/m^2 (%)	17.1% (193)	21.3% (720)	0.228	40.9% (220)	66.3% (86)	**<0.001**
Cephalometrics						
SNA (degrees)	79.8 ± 3.4 (66)	80.3 ± 3.0 (247)	0.376	80.2 ± 3.0 (219)	80.0 ± 3.5 (86)	0.635
SNA < 80 degrees (%)	42.4% (66)	37.2% (247)	0.477	37.3% (220)	43.0% (86)	0.364
SNB (degrees)	76.7 ± 4.1 (66)	77.3 ± 3.7 (247)	0.292	77.0 ± 3.9 (220)	77.4 ± 3.6 (86)	0.471
SNB < 80 degrees (%)	72.7% (66)	74.6% (247)	0.753	73.2% (220)	76.7% (86)	0.564
PAS (mm)	5.4 ± 2.1 (66)	5.4 ± 2.3 (240)	0.938	5.4 ± 2.3 (220)	5.3 ± 2.0 (86)	0.658
Polysomnography						
RDI (events/hour)	31.0 ± 25.2 (195)	41.2 ± 23.5 (746)	**<0.001**	52.9 ± 27.5 (220)	63.4 ± 24.1 (86)	**0.001**
RDI ≥ 20 events/hr (%)	55.4% (195)	82.7% (746)	**<0.001**	86.4% (220)	100.0% (86)	**<0.001**
SpO_2 Nadir (%)	85.5 ± 9.1% (193)	82.9 ± 10.2% (736)	**0.001**	75.0 ± 10.0 (220)	69.4 ± 10.4 (86)	**<0.001**
ODI (desaturations/hour)	27.0 ± 27.7 (66)	34.2 ± 27.2 (240)	0.066	28.5 ± 26.8 (220)	43.1 ± 26.2 (86)	**<0.001**
ODI ≥ 20 events/hr (%)	43.9% (66)	59.2% (240)	**0.035**	49.1% (220)	73.3% (86)	**<0.001**
Post-MMA						
BMI (kg/m^2)	27.1 ± 4.7 (181)	27.8 ± 4.3 (678)	0.055	29.7 ± 5.7 (219)	32.4 ± 5.5 (86)	**<0.001**
% Change in BMI (%)	-0.9 ± 2.5% (181)	-0.6 ± 1.7% (672)	0.108	-0.1 ± 0.7 (219)	-0.1 ± 0.3 (86)	0.401
Cephalometrics						
SNA (degrees)	82.0 ± 3.0% (66)	81.4 ± 3.2 (239)	0.202	82.0 ± 3.0 (219)	80.5 ± 34.7 (86)	**0.001**
SNA < 80 degrees (%)	19.7% (66)	24.7% (239)	0.513	18.7% (219)	36.0% (86)	**0.002**
Change in SNA (degrees)	2.1 ± 3.0 (66)	1.3 ± 2.3 (239)	**0.030**	1.8 ± 2.7 (219)	0.5 ± 1.5 (86)	**<0.001**
SNB (degrees)	78.4 ± 3.2 (66)	78.4 ± 3.4 (239)	0.913	78.5 ± 3.2 (219)	78.0 ± 3.6 (86)	0.230
SNB < 80 degrees (%)	62.1% (66)	65.7% (239)	0.662	62.1% (219)	72.1% (86)	0.111
Change in SNB (degrees)	1.7 ± 2.6 (66)	1.2 ± 2.3 (239)	0.138	1.5 ± 2.5% (219)	0.6 ± 1.8% (86)	**<0.001**
PAS (mm)	9.1 ± 2.1 (66)	8.3 ± 2.6 (239)	**0.013**	8.9 ± 2.3 (219)	7.3 ± 2.6 (86)	**<0.001**
Change in PAS (mm)	3.7 ± 2.3 (66)	2.9 ± 2.4 (239)	**0.024**	3.5 ± 2.4 (219)	2.0 ± 2.0 (86)	**<0.001**
Polysomnography						
RDI (events/hour)	2.6 ± 1.2 (195)	16.4 ± 15.2 (746)	**<0.001**	9.0 ± 7.5 (220)	42.4 ± 25.7 (86)	**<0.001**
% Change in RDI (%)	-86.1 ± 11.0% (195)	-55.0 ± 33.2% (746)	**<0.001**	-76.6 ± 30.9% (220)	-29.4 ± 37.6% (86)	**<0.001**
RDI < 20 events/hr (%)	100.0% (195)	88.8% (746)	**<0.001**	94.1% (220)	17.4% (86)	**<0.001**
SpO_2 Nadir (%)	91.6 ± 3.3% (192)	88.3 ± 6.8% (735)	**<0.001**	87.2 ± 3.1% (220)	74.8 ± 9.8% (86)	**<0.001**
% Change in SpO_2 Nadir (%)	8.4 ± 11.4% (192)	7.7 ± 12.2 (730)	0.479	18.4 ± 16.9% (220)	9.1 ± 15.4% (86)	**<0.001**
ODI (desaturations/hour)	0.4 ± 0.7 (66)	9.7 ± 17.0 (240)	**<0.001**	1.1 ± 1.4 (220)	24.6 ± 21.4 (86)	**<0.001**
% Change in ODI (%)	-95.8 ± 16.7% (66)	-43.8 ± 225.0% (240)	**<0.001**	-87.3 ± 34.1% (220)	27.7 ± 3.6% (86)	**0.004**
RDI Surgical Success (%)†	100.0% (195)	66.1% (746)	**<0.001**	92.7% (220)	16.3% (86)	**<0.001**
ODI Surgical Success (%)†	98.5% (66)	74.2% (240)	**<0.001**	93.6% (220)	43.0% (86)	**<0.001**

** Surgical cure defined as an RDI (or ODI) < 5 events/hour post-MMA. Mean (or percent) ± standard deviation. The total number of patients is shown in parentheses. Abbreviations: BMI (body mass index), MMA (maxillomandibular advancement), ODI (oxygen desaturation index), PAS (posterior airway space – base of tongue), RDI (respiratory disturbance index), SNA (sella-nasion-Point A angle), SNB (sella-nasion-Point B angle), SpO_2 (pulse oxyhemoglobin saturation). † Surgical success defined as the percent of subjects with an RDI (or ODI) < 20/hour and a ≥ 50% reduction in the RDI (or ODI) post-MMA. ‡ Equal variances not assumed for p-value calculation. Fisher's exact 2-sided p-value used for categorical data.*

Table 5. Predictors of Post-MMA OSA Surgical Success*.

Predictor	Post MMA			Post MMA		
	RDI Success (n=688; 73.1%)	No Success (n=253; 26.9%)	P-value‡	ODI Success (n=243; 79.4%)	No Success (n=63; 20.6%)	P-value‡
Pre-MMA						
Age (years)	38.2 ± 14.3 (688)	44.2 ± 12.9 (253)	**<0.001**	46.3 ± 12.0 (243)	51.5 ± 9.9 (63)	**0.001**
Age > 50 years (%)	24.4% (688)	37.5% (253)	**<0.001**	40.7% (243)	54.0% (243)	0.065
Male (%)	75.7% (688)	84.6% (253)	**0.003**	93.0% (243)	100.0% (63)	**0.028**
BMI (kg/m²)	27.2 ± 4.1 (668)	29.0 ± 4.6 (245)	**<0.001**	30.1 ± 5.8 (243)	32.3 ± 5.7 (63)	**0.010**
BMI > 30 kg/m² (%)	15.7% (668)	33.1% (245)	**<0.001**	44.4% (243)	61.9% (63)	**0.016**
Cephalometrics						
SNA (degrees)	80.2 ± 3.0 (219)	80.0 ± 3.5 (94)	0.631	80.1 ± 3.0 (243)	80.0 ± 3.6 (63)	0.865
SNA < 80 degrees (%)	37.9% (219)	39.4% (94)	0.801	38.3% (243)	41.3% (63)	0.666
SNB (degrees)	77.1 ± 3.9 (219)	77.3 ± 3.6 (88)	0.637	77.0 ± 3.8 (243)	77.5 ± 3.8 (63)	0.353
SNB < 80 degrees (%)	72.5% (218)	78.4% (88)	0.315	74.5% (243)	73.0% (63)	0.872
PAS (mm)	5.3 ± 2.2 (218)	5.5 ± 2.2 (88)	0.461	5.4 ± 2.3 (243)	5.3 ± 2.0 (63)	0.696
Polysomnography						
RDI (events/hour)	38.1 ± 23.5 (688)	41.8 ± 26.0 (253)	**0.049**	52.9 ± 27.5 (220)	63.4 ± 24.1 (86)	0.954
RDI ≥ 20 events/hr (%)	76.5% (688)	78.7% (253)	0.541	86.4% (220)	100.0% (86)	0.056
SpO_2 Nadir (%)	84.1 ± 9.4% (688)	81.6 ± 11.3% (250)	**0.002**	75.0 ± 10.0 (220)	69.4 ± 10.4 (86)	0.253
ODI (desaturations/hour)	30.8 ± 26.6 (218)	37.0 ± 28.9 (88)	0.084	28.5 ± 26.8 (220)	43.1 ± 26.2 (86)	0.991
ODI ≥ 20 events/hr (%)	54.6% (218)	59.1% (88)	0.525	49.1% (220)	73.3% (86)	0.088
Post-MMA						
BMI (kg/m²)	27.1 ± 4.2 (630)	29.0 ± 4.8 (229)	**<0.001**	30.0 ± 5.7 (242)	32.1 ± 5.7 (63)	**0.010**
% Change in BMI (%)	-0.8 ± 1.7% (624)	-0.4 ± 2.4% (229)	**0.031**	-4.2 ± 2.1% (242)	-3.7 ± 9.5% (63)	0.774
Cephalometrics						
SNA (degrees)	82.1 ± 2.8 (217)	80.1 ± 3.6 (88)	**<0.001**	81.9 ± 3.0 (242)	80.2 ± 3.5 (63)	**0.001**
SNA < 80 degrees (%)	17.5% (217)	38.6% (88)	**<0.001**	19.4% (242)	39.7% (63)	**0.001**
Change in SNA (degrees)	1.9 ± 2.7 (217)	0.3 ± 1.1 (88)	**<0.001**	1.8 ± 2.7 (242)	0.2 ± 0.9 (63)	**<0.001**
SNB (degrees)	78.7 ± 3.1 (217)	77.7 ± 3.7 (88)	**0.027**	78.6 ± 3.2 (242)	77.7 ± 3.6 (63)	0.097
SNB < 80 degrees (%)	60.8% (217)	75.0% (88)	**0.024**	62.4% (242)	74.6% (63)	0.077
Change in SNB (degrees)	1.6 ± 2.5 (217)	0.4 ± 1.4 (88)	**<0.001**	1.6 ± 2.5 (242)	0.2 ± 1.2 (63)	**<0.001**
PAS (mm)	9.0 ± 2.2 (217)	7.1 ± 2.6 (88)	**<0.001**	8.9 ± 2.3 (242)	6.8 ± 2.4 (63)	**<0.001**
Change in PAS (mm)	3.7 ± 2.2 (217)	1.6 ± 2.0 (88)	**<0.001**	3.5 ± 2.3 (242)	1.5 ± 1.7 (63)	**<0.001**
Polysomnography						
RDI (events/hour)	7.9 ± 4.7 (688)	29.0 ± 20.3 (253)	**<0.001**	11.4 ± 11.2 (243)	45.3 ± 28.2 (63)	**<0.001**
% Change in RDI (%)	-75.2 ± 13.4% (688)	-23.9 ± 39.0% (253)	**<0.001**	-74.9 ± 30.1% (243)	-18.6 ± 37.9 (63)	**<0.001**
RDI < 20 events/hr (%)	100.0% (688)	36.0% (253)	**<0.001**	85.6% (243)	22.2% (63)	**<0.001**
SpO_2 Nadir (%)	90.5 ± 3.7% (678)	84.9 ± 9.5% (249)	**<0.001**	86.3 ± 4.3% (243)	73.8 ± 11.1% (63)	**<0.001**
% Change in SpO_2 Nadir (%)	8.9 ± 12.5% (673)	4.9 ± 10.1% (249)	**<0.001**	18.8 ± 16.4% (243)	4.1 ± 13.9% (63)	**<0.001**
ODI (desaturations/hour)	1.5 ± 2.3 (218)	23.0 ± 22.4 (88)	**<0.001**	2.4 ± 3.8 (243)	28.2 ± 24.4 (63)	**<0.001**
% Change in ODI (%)	-90.0 ± 22.4% (218)	31.8 ± 359.1% (88)	**0.002**	-91.8 ± 11.6% (243)	87.0 ± 414.0% (63)	**0.001**
RDI Surgical Success (%)†	28.3% (688)	0.0% (253)	**<0.001**	26.7% (243)	1.6% (63)	**<0.001**
ODI Surgical Success (%)†	93.6% (688)	18.2% (88)	**<0.001**	84.8% (243)	22.2% (63)	**<0.001**

** Surgical success defined as the percent of subjects with an RDI (or ODI) < 20/hour and a ≥ 50% reduction in the RDI (or ODI) post-MMA. Mean (or percent) ± standard deviation. The total number of patients is shown in parentheses. Abbreviations: BMI (body mass index), MMA (maxillomandibular advancement), ODI (oxygen desaturation index), PAS (posterior airway space –base of tongue), RDI (respiratory disturbance index), SNA (sella-nasion-Point A angle), SNB (sella-nasion-Point B angle), SpO_2 (pulse oxyhemoglobin saturation). † Surgical cure defined as an RDI (or ODI) < 5 events/hour post-MMA. ‡ Equal variances for linear data not assumed for p-value calculation. Fisher's exact 2-sided p-value used for categorical data.*

Table 6. First 500 vs Last 510 MMA Characteristics*.

	First MMA N=500	Last MMA N=510	P-value
Characteristics			
Age	44.8 ± 13.0 (500)	34.6 ± 13.7 (510)	**<0.001**
Male Gender (%)	84.8% (500)	69.4% (510)	**<0.001**
PreMMA BMI (kg/m²)	29.3 ± 5.1 (495)	25.8 ± 1.8 (481)	**<0.001**
PostMMA BMI (kg/m²)	29.2 ± 5.1 (491)	25.5 ± 1.7 (423)	**<0.001**
Percent Change BMI	-0.3 ± 2.2% (489)	-1.0 ± 2.3% (419)	**<0.001**
PreMMA Polysomography			
RDI (events/hour)	48.0 ± 26.3 (498)	28.4 ± 16.8 (507)	**<0.001**
RDI ≥ 30/hr (%)	69.9% (498)	36.7% (507)	**<0.001**
SpO_2 Nadir (%)‡	78.6 ± 11.2% (491)	88.8 ± 4.4% (495)	**<0.001**
ODI (desaturations/hour)	32.6 ± 27.4 (306)	-	NA
ODI ≥ 30/hr (%)	47.7% (306)	-	NA
PostMMA Polysomography			
RDI (events/hour)	17.1 ± 18.3 (484)	9.9 ± 7.8 (458)	**<0.001**
RDI ≥ 30/hr (%)	13.4% (484)	3.3% (458)	**<0.001**
Percent Change RDI (%)	-59.0 ± 40.3% (484)	-64.0 ± 21.4% (457)	**0.017**
SpO_2 Nadir (%)‡	86.0 ± 7.3% (479)	92.1 ± 2.7% (449)	**<0.001**
Percent Change SpO_2 Nadir (%)	11.5 ± 15.5% (476)	3.9 ± 3.8 (449)	**<0.001**
ODI (desaturations/hour)†	7.7 ± 15.5 (306)	-	NA
ODI ≥ 30/hr (%)	8.5% (306)	-	NA
Percent Change ODI (%)	-55.0 ± 2.0 (306)	-	NA
PreMMA Cephalometrics†			
SNA (degrees)	80.2 ± 3.1 (321)	-	NA
SNB (degrees)	77.1 ± 3.8 (306)	-	NA
PAS (mm)	5.4 ± 2.2 (306)	-	NA
PostMMA Cephalometrics†			
SNA (degrees)	81.5 ± 3.2 (305)	-	NA
SNB (degrees)	78.4 ± 3.3 (305)	-	NA
PAS (mm)	8.4 ± 2.5 (305)	-	NA
RDI Surgical Cure (%)#	17.8% (484)	23.9% (457)	**0.024**
ODI Surgical Cure (%)#,†	71.9% (306)	-	NA
RDI Surgical Success (%)#	66.7% (484)	77.9% (457)	**<0.001**
ODI Surgical Success (%)#,†	79.4%	-	NA

** Plus-minus values are mean (or percent) ± standard deviation. Values in parenthesis are the number of patients evaluated. Abbreviations: BMI (body mass index), MMA (maxillomandibular advancement), ODI (oxygen desaturation index), PAS (posterior airway space – base of tongue), PNS-P (distance of posterior nasal spine to the tip of the soft palate), RDI (respiratory disturbance index), REM (rapid eye movement), SNA (sella-nasion-Point A angle), SNB (sella-nasion-Point B angle), SpO_2 (pulse oxyhemoglobin saturation). † ODI and cephalometric data only available on a subset of MMA patients that were exclusively within the first 500 subjects studied. ‡ The SpO_2 nadir is the lowest oxyhemoglobin saturation measured during sleep. Only patients with both pre- and post-MMA SpO_2 nadir are included. # Surgical cure defined an RDI (or ODI) < 5 events/hour post-MMA. Surgical success defined as the percent of subjects with an RDI (or ODI) < 20/hour and a ≥ 50% reduction in the RDI (or ODI) post-MMA.*

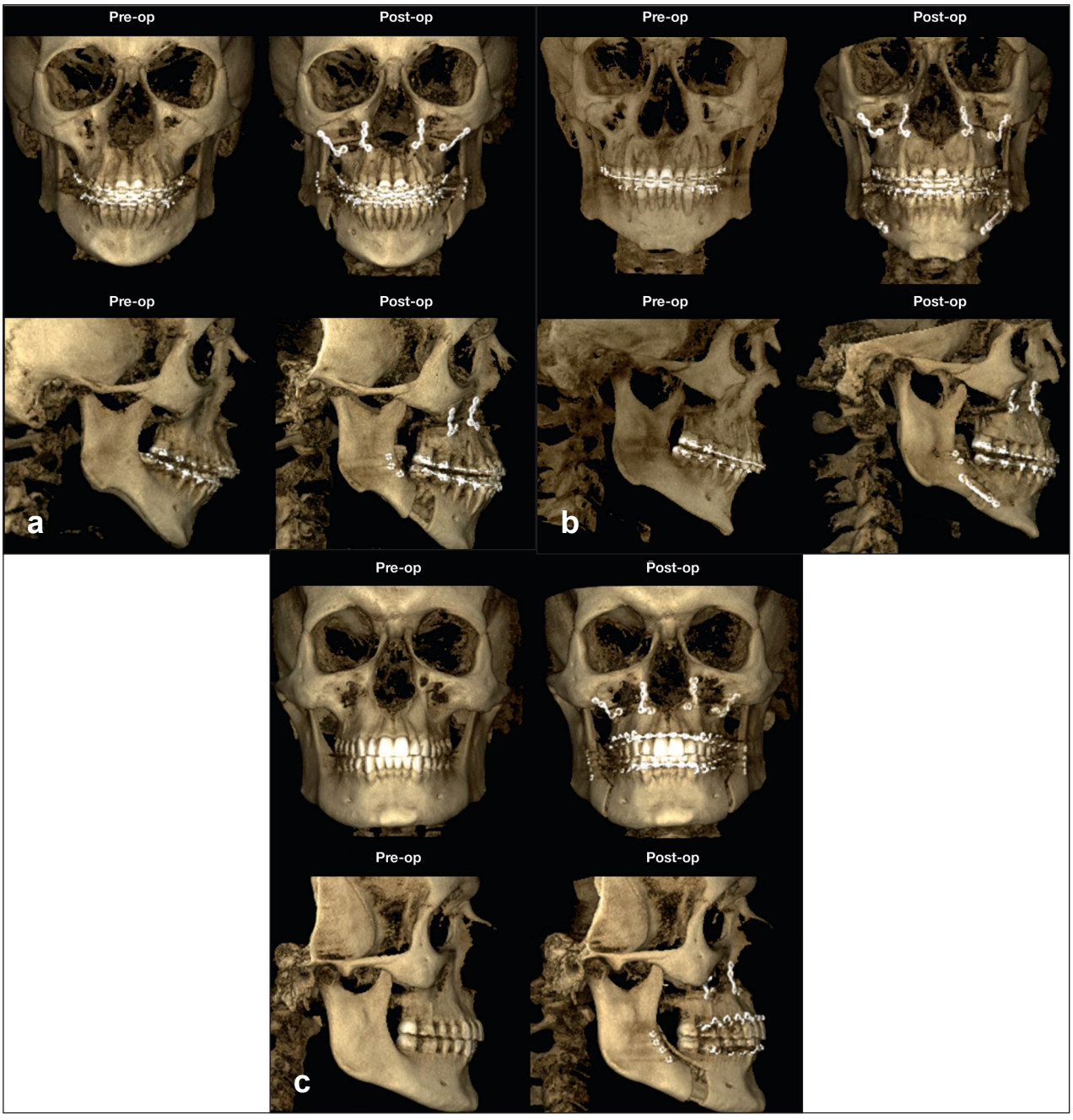

Figure 2

(a-c) Pre- and post-MMA imaging demonstrating different surgical plans but the main objective of maximizing the advancement within the physiologic limitation of the soft tissues is maintained.

ment option in properly selected patients. We have seen a trend of younger patients with less severe OSA increasingly opting for MMA as the treatment of choice. The improved surgical outcome with greater percentage reduction in RDI and surgical success/cure in patients with younger age, lower RDI and lower BMI are quite evident when comparing the first 500 patients versus the later 510 patients (Table 6). The differences in the patient population reflected the clinical insights gained over the years in the patient selection for MMA. The improved outcome is also likely related to the advances in surgical expertise and technique in the more recently treated patients.

The RDI was chosen as one of the primary outcome variables. This is due to the improved understanding of the impact of respiratory effort-related arousals (RERA) in causing sleep fragmentation affecting daytime function and quality of life[1,6,7]. The results clearly demonstrate that MMA significantly reduces the RDI in the majority of the patients where the overall surgical success and surgical cure based on RDI were 73.1% and 20.7%, respectively. The RDI outcome compares favorably to the meta-analysis from 2016 with the rate of success and cure of 44 (64.7%) and 13 (19.1%), respectively[31]. This could be related to the small sample size in the meta-analysis with only 68 patients as well as the heterogeneity of the pooled data[31]. The comparison of the first 500 patients to the more recent 510 patients also showed that the outcome has improved in the rate of surgical success (77.9% versus 66.7%) and surgical cure (23.9% versus 17.8%). Again, the improved outcome could be related to better patient selection and surgical execution.

The maxillofacial anatomy as a risk factor in patients with OSA based on cephalometric data has been published extensively since the initial report by Guilleminault's group in 1986[9]. The analysis on cephalometric measurements in this study showed that a greater increase in SNA, SNB and PAS postoperatively resulted in improved outcome (Table 5). This finding suggests that greater advancement distance results in greater OSA improvement. Therefore, it must be emphasized that the goal of MMA is not to "normalize" cephalometric measurements since many patients with "normal" measurements have OSA[18] but rather, it is to maximize the advancement distance in optimizing airway expansion. This objective must be adhered to because OSA remained even when advancement was maximized. It is recognized that lower OSA severity, neurocognitive symptoms and cardiovascular sequelae remain[2,4,5]. Clearly, maximizing the advancement must be balanced with the alteration of facial esthetics. Therefore, the surgical plan must be a collaborative decision between the surgeon and the patient. A comprehensive discussion of prognostic factors and the impact of advancement on airway and esthetics is essential so an ideal surgical plan can be formulated based on a collaborative effort between the patient and the surgeon (Fig. 2).

5. Conclusions

MMA is an effective treatment to improve OSA, but the result can vary. Patient selection based on favorable prognostic factors and maximizing the advancement distance can improve outcomes.

Links of interest

The authors declare that they have no interest in the data published in this article.

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