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Surgical changes of posterior airway space in obstructive sleep apnea

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There are numerous medical and surgical treatment modalities for the management of the sleep apnea patient. Among the medical treatments, weight loss and positive pressure therapy are considered to be the most important. Surgical treatment is directed at increasing the posterior airway space. Among the surgical procedures, tracheostomy, uvulopalatopharyngoplasty (UPPP), and maxillofacial skeletal procedures are the most common.

Positive pressure therapy during sleep is considered effective in limiting obstructive events during sleep. Pressure is titrated to the desired value that eliminates upper airway collapse during nocturnal polysomnography; however, despite a reported 65% to 90% compliance rate with positive airway pressure therapy when compliance is assessed by subjective patient reports, long-term compliance is less than optimal when objectively monitored. Kribbs et al [1] used continuous positive airway pressure (CPAP) machines that contained a microprocessor and a monitor that measured actual pressure at the mask for every minute of each 24-hour day for an average of 106 days per patient. Patients were not aware of the monitor inside the CPAP machines. Although 60% of patients claimed to use CPAP nightly, only 16 of 35 (46%) met the criteria for regular use, which was defined as at least 4 hours of CPAP therapy administered on 70% of the days monitored [1]. There is proof that part-time use of CPAP is not satisfactory in controlling obstructive sleep apnea (OSA) [2,3]. Intolerance of CPAP therapy because of poor mask fit, claustrophobia, difficulty with exhaling, air temperature (too cold or too warm), or machine noise as well as the cumbersomeness and inconvenience in general may lead to decreased compliance. Acceptance of treatment may be improved with bilevel positive airway pressure (BiPAP), although a study published by Reeves-Hoché and coworkers [4] indicated that in patients who do not accept therapy for home use, compliance is the same for both CPAP and BiPAP systems.

Consequently, the option of surgery should be offered to OSA patients who fail to comply with home positive pressure therapy and continue to suffer from heavy snoring, fragmented sleep, excessive daytime somnolence, and cognitive changes.

Primary procedures for the surgical treatment of OSA

Tracheostomy

Permanent tracheostomy was the first efficacious surgical procedure performed for the treatment of OSA. In the 1970s and 1980s, it was by far the most commonly performed surgical procedure for this problem. Tracheostomy has a success rate of almost 100% in reversing the signs and symptoms of OSA because it bypasses all the potential sites of obstruction in the upper airway. After tracheostomy there is a rapid and striking reduction in daytime somnolence. Additionally, hypoxemia, apnea, pulmonary hypertension, bradycardia, and cardiac dysrhythmias all diminish dramatically with the procedure. The psychologic toll on the patients, however, is sometimes devastating; in addition, there is esthetic disfigure-

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ment and risk for more serious complications such as tracheal stenosis, erosion of vessel walls, and recurrent bronchitis. Therefore, the procedure is used mainly as an interim treatment until surgical reconstruction of the upper airway can be completed. The goal is to decannulate the patient eventually [5]. Simmons et al [6] suggested that tracheostomy should still be the primary treatment for all patients who have life-threatening cardiac dysrhythmias and for those who have frequent oxygen desaturations below 50% during apneic episodes [5,6].

UPPP

Ikematsu initially described UPPP in 1964 for the treatment of habitual snoring [6a]. When he investigated habitual snorers, he found that 91% had narrowing of the oropharynx caused by an elongated soft palate and uvula as well as redundant lateral pharyngeal mucosa. Excision of the redundant mucosa in the tonsillar pillars and partial excision of the uvula eliminated snoring in 96% of his patients. With minor modifications Fujita et al first performed the procedure in 1981 for the treatment of OSA [6b]. The procedure was designed to enlarge the potential airspace in the oropharynx by performing a tonsillectomy and adenoidectomy, excising the uvula and redundant lateral pharyngeal wall mucosa, and resecting 8 to 15 mm along the posterior border of the soft palate. UPPP is excellent for the control of snoring; in addition, several reports [5] have shown significant objective improvement in the respiratory distress index (RDI), and hemoglobin desaturation levels on the postoperative polysomnogram range from 41% to 66%.

Sher [7] reported in 1996 a success rate of 40% for UPPP alone, which is increased to 60% if the procedure is combined with genioglossus advancement and hyoid myotomy/suspension (GAHM). He also suggested that maxillomandibular advancement should be offered as a primary procedure to non-obese, skeletally deficient patients with moderately severe OSA, whereas obese patients with more severe OSA should receive adjunctive soft tissue procedures such as UPPP [7]. It is now well recognized that although most patients with OSA demonstrate retropalatal narrowing of their airway, this is not the only area of the pharynx that collapses during sleep. Collapse occurs most of the time at multiple sites, and the failure of UPPP to offer a cure to most sleep apnea patients is attributed to the inability of the procedure to control obstruction in other sites of the upper airway besides the retropalatal area [8–16]. Suto and coworkers [14] used ultrafast MRI in patients with sleep apnea as well as in healthy control subjects. The subjects were scanned while awake and during sleep induced with hydroxyzine. The results of this study showed that obstruction occurs most often in the retropalatal area, although frequently there is an additional site of obstruction [14].

Shepard and Thawley [15] studied 18 patients with OSA using overnight polysomnography with simultaneous pressure monitoring in the posterior nasopharynx, oropharynx, hypopharynx, and esophagus. They concluded that the upper airway collapses in the velopharyngeal/retropalatal area in approximately 50% of the cases. In other cases the obstruction can start initially in the glossopharyngeal/retroglossal area. As soon as it appears, the obstruction can extend to involve adjacent segments of the upper airway. This happens more significantly during rapid eye movement (REM) sleep secondary to the pronounced atonia of the upper airway dilator muscles [15]. The results of Morrison et al [16] show that the retropalatal area is the site of primary narrowing in 80% of the patients; however, two or even more sites of narrowing are observed in 82% of the patients. Sher et al [17] showed in 1985 that UPPP is successful when it is performed on patients who obstruct only in the retropalatal section of their oropharynx as evidenced by a preoperative Mueller's maneuver. Patients were selected for the procedure based on the results of a preoperative Mueller's maneuver. Of these patients 87%, had $>50\%$ decrease in their RDI [17]. In 1990 Riley et al [18] reported that UPPP most frequently failed in patients with mandibular retrognathia (Sella-Nasion-B (SNB) point angle $<74°$) and morbid obesity (body mass index [BMI] >33 kg/m^2]. Ryan et al [19] published the data of a well-designed prospective study that showed an 83% success rate for UPPP for patients selected from preoperative three-dimensional CT reconstructions of their airway to have large tongue volume, decreased upper airway to tongue volume ratio, and decreased upper airway to soft palatal volume ratio.

The Stanford protocol for surgical reconstruction of the upper airway

In 1986, on the basis of previous surgical experience, Riley, Powell, and Guilleminault [20] first introduced to clinical practice a two-phase protocol for surgical reconstruction of the sleep apneic airway. The protocol entailed a presurgical evaluation that included a physical examination, cephalometric analysis, and fiberoptic pharyngoscopy. The site of obstruction was identified with the help of Mueller's maneuver, and surgery was directed to the obstructed sites. After the presurgical evaluation each patient was classified by the site of obstruction according to Fujita: type I, retropalatal; type II, retropalatal and retroglossal; and type III, only retroglossal. Patients were classified as positive for retropalatal obstruction when fiberoptic examination showed that a redundant soft palate collapsed against the pharyngeal wall with the Mueller maneuver and cephalometric analysis showed elongation of the soft palate. Retroglossal obstruction was positive when the base of the tongue collapsed against the posterior pharyngeal wall and restricted visualization of the larynx during fiberoptic examination or when the cephalometric analysis demonstrated a narrow posterior airway space (PAS). Patients with OSA and mandibular skeletal deficiency (SNB angle $< 76°$) on cephalometric analysis almost uniformly have a narrow PAS and base of tongue obstruction.

In phase I surgery, patients with type I obstruction (soft palate) received UPPP. Patients with type III obstruction (base of tongue) received GAHM. With this procedure the attachments of the genioglossus muscle to the genial tubercles are advanced anteriorly while the body of the hyoid bone is freed from the attachments of the infrahyoid strap muscles and suspended 1 to 1.5 cm anteriorly and superiorly from the inferior border of the mandibular symphysis. Severe dysphagia can be created if the hyoid is suspended more than 1.5 cm [21]. Patients with type II obstruction received during phase I surgery both a UPPP and GAHM. Follow-up polysomnograms were obtained 6 months after phase I surgery, and poor responders were offered phase II surgery, which consisted of surgical advancement of the maxilla and the mandible [2].

In 1993 the same authors [2] reported on the results of this surgical protocol. Criteria for success were considered a postoperative RDI less than 20 per hour with at least a 50% reduction over the preoperative study and lowest hemoglobin oxygen saturation levels (LSAT) equivalent to those seen with nasal CPAP. Most of the 239 patients who entered phase I therapy were type II and, therefore, received a UPPP and a GAHM. The patients who received only a UPPP and were treated successfully in general had long redundant soft palates, no mandibular deficiency (SNB >78), and normal airway space at the base of the tongue (PAS >10 mm). In contrast, the patients with a successful result after an isolated GAHM had mandibular deficiency (SNB < 78), normal palatal tissue without tonsils, and narrow airway space at the base of the tongue (PAS < 6 mm). Overall, 61% of these patients were treated successfully. The majority of the patients who had unsuccessful phase I treatment had severe OSA (mean RDI of 62 per hour) and morbid obesity (mean BMI 32.3 kg/m^2). Only 24 of the 94 patients who underwent unsuccessful phase I therapy elected phase II therapy, with a success rate of 97% [2]. The same group of authors reported recently on 21 patients with morbid obesity (BMI >40 kg/m^2) and severe OSA (RDI >40 per hour) who underwent the same two-phase surgical protocol with a success of 81% [22].

Maxillomandibular advancement (MMA)

Isolated reports of using orthognathic surgery for the treatment of OSA first appeared in the literature in the late 1970s and early 1980s [23,24]. Over the next 10 years, combined advancement of the maxilla, mandible, and chin became the surgical procedure of choice for the treatment of OSA. The technique includes a standard Le Fort I osteotomy in combination with bilateral sagittal split ramus osteotomies for the simultaneous advancement of the maxilla and mandible. In many cases, an advancement geniotomy, with or without hyoid myotomy and suspension, is also performed. Waite et al [25] reported on 23 OSA patients treated with MMA along with a high sliding geniotomy without hyoid myotomy and suspension. Originally believed to be indicated only in major skeletal deficiencies after other surgical options failed, MMA now is recommended as a primary surgical option for OSA.

MMA is indicated for patients with (1) retroglossal obstruction, (2) severe OSA (RDI >50 per hour), (3) hemoglobin oxygen desaturation lower than 85%, (4) morbid obesity, and (5) failure to respond to other treatment. The procedure is also indicated for maxillomandibular hypoplasias, believed to cause diminished posterior airway space leading to obstruction [26]. A surgical advancement of 10 mm is usually performed. This is an arbitrary value that corresponds to the greatest forward movement that is technically feasible in most cases for the maxilla; however, Paoli et al [27] recently reported on a case of a 44-year-old male patient with severe OSA (preoperative RDI of 88 per hour) whom they treated with mandibular elongation by using intraoral mandibular distraction devices. In this way the amount of mandibular advancement required to eliminate the obstructive events was titrated to effect. The final position of the mandible was 12 mm anteriorly with a postdistraction RDI of 23/hour. This was followed up by a maxillary Le Fort I advancement to the desired dental occlusion. The final polysomnogram revealed an RDI of 7 per hour [27].

The reported success rates of MMA by various authors are summarized in Table 1. Individual reports need to be looked at carefully because most of the time

Table 1
Reported success rate of maxillomandibular advancement surgery

Author	Institution	Patients	Success	Criteria for success
[a]Waite et al [25]	U.A.B.	23	65%	RDI < 10, improvement of symptoms (97% benefited from the procedure)
[a]Riley et al [18]	Stanford University	40 (phase II)	97%	RDI < 20, 50% decrease of RDI, normal or near normal SaO_2
[a]Riley et al [2]	Stanford University	24 (phase II)	100%	RDI < 20, 50% decrease of RDI, LSAT equivalent to nasal CPAP
Hochban et al [28]	Marburg University	21	95%	RDI < 10 (no patient with BMI >30 kg/m^2)
Tiner [5]	University of Texas	22	95%	RDI < 20, improvement of symptoms
[a]Prinsell [29]	Private practice, GA	50	100%	RDI < 15, AI < 5, LSAT >80%, >60% decrease in RDI and AI[b]
[a]Li et al [22]	Stanford University	21 (phase II)	81%	RDI < 20 (all patients with BMI >40 kg/m^2)

Abbreviations: BMI, body mass index; CPAP, continuous positive airway pressure; LSAT, lowest hemoglobin oxygen saturation; RDI, respiratory distress index; SaO_2, hemoglobin oxygen saturation; UAB, University of Alabama at Birmingham.

[a] Report on combined surgical procedures (maxillomandibular advancement + uvulopalato-pharyngoplasty +/− geniotomy advancement or genioglossus advancement with hyoid myotomy/suspension).

[b] AI = apnea index (number of apneas per hour of sleep).

MMA is performed on a patient who has already undergone unsuccessful UPPP. Therefore, the reported success rate will be essentially that of a combined procedure and will not represent the true success rate of MMA alone.

Secondary procedures for the surgical treatment of OSA

Nasal surgery

In patients diagnosed with OSA, nasal procedures aim at decreasing the resistance against the passage of air by increasing the volume of the nasal cavity. Potential reasons for nasal obstruction include a deviated nasal septum and hypertrophic inferior turbinates obliterating the inferior and middle meatuses, which represents the main route followed by the inspired air stream. Septoplasty and inferior turbinectomy may be performed via endonasal approaches or, alternatively, if surgery also includes maxillary advancement, they may be conveniently performed after maxillary downfracture, which greatly facilitates access to these structures. Resection of the deviated portion of the nasal septum may be attempted after careful elevation of the mucoperichondrium that envelops the nasal septum, whereas excision of the bulbous anterior aspect of the inferior turbinate requires a longitudinal incision along the mucoperiosteum of the floor of the nasal cavity. After conclusion of the septoplasty, use of a quilting 4/0 plain gut suture prevents the possibility of a septal hematoma. The longitudinal incisions along the nasal floors may be closed with running 4/0 chromic gut sutures. This is performed prior to maxillary rigid fixation, whereas after maxillary repositioning, a 2/0 polyglactin suture is required to secure the caudal aspect of the nasal septum to the midline of the premaxilla in the area of the anterior nasal spine, which prevents buckling of the nasal septum laterally, thus restricting the ipsilateral nasal passage.

At the conclusion of maxillary orthognathic procedures the nasal musculature usually is reoriented with the help of a sling suture, which has the purpose of preventing potential widening of the alar base. This strategy is generally avoided when the indication of maxillary surgery is OSA. The reason is that a postoperative decrease in the alar width may be beneficial from a cosmetic standpoint; however, it may increase resistance against the passage of air, which for a sleep apnea patient represents a complication. The same concept lies behind performing a piriformplasty. With this procedure the piriform aperture of the nasal cavity is accessed and visualized via a maxillary vestibular incision and widened with the help of rotating instruments. This results in less resistance against the passage of air through the nasal valves.

Nasopharyngeal and oropharyngeal soft tissue procedures

It is recognized that the presence of hypertrophic adenoids and pharyngeal tonsils is the main cause of OSA in the pediatric population. Even in adult sleep apnea patients, the roof of the nasopharynx should not be missed during the preoperative clinical and radiographic evaluation. A good quality lateral cephalometric radiograph obtained for evaluation of the maxillofacial skeletal structures sometimes reveals hypertrophic adenoids inferiorly and anteriorly to the sphenoid sinus. CT images of the upper airway, however, are more reliable at visualizing this, especially if sagittal reconstructions are available. Treatment consists of curettage of the hypertrophic lymphoepithelial tissue, which may be performed as an adjunct to other upper airway reconstructive surgical procedures.

Obstruction of the upper airway at the retroglossal level occurs in cases of mandibular deficiency. Retroposition is best demonstrated in an infant born with the Pierre-Robin sequence. In these cases it may be beneficial to temporarily suture the tip of the tongue to the chin to avoid the necessity of a tracheostomy. Later, spontaneous mandibular growth or mandibular corrective surgery in the form of mandibular distraction osteogenesis or both can permanently alleviate the problem.

A much more common type of retroglossal obstruction is seen in obese individuals whose tongue size and volume have been shown by MRI to be increased compared to non-obese control subjects. In a few selected cases tongue reduction in the form of a midline "keyhole" tongue resection may be advocated for sleep apneic morbidly obese patients. The procedure may be performed as a cold steel excision or thermally with the use of electrocautery or laser to avoid blood loss. The laser excision has the advantage over the electrocautery of provoking considerably less muscle twitching, and thus some surgeons find it more convenient. It is important after the excision to carefully reapproximate the tissues in two layers (muscle and superficial mucosa) with 2/0 or 3/0 polyglactin sutures to avoid postoperative tissue breakdown and a bifid tongue tip.

Subjective data suggested that the laser-assisted uvulopalatoplasty (LAUP) was effective as a treatment of snoring [30], which led to a subtle expansion of the indications for LAUP to include OSA treatment. LAUP has the advantage over UPPP in that it is performed on an outpatient clinic basis under local anesthesia supplemented with intravenous sedation. It is less invasive than UPPP because it addresses redundant tissues of the soft palate only. Most commonly it consists of a circumferential excision of an elongated uvula and laser ablation of tissue along the free posterior border of the soft palate. The results are scarification and contracture during the healing process, which decrease the size of the soft palate. The fundamental shortcoming of palatal surgical procedures, such as LAUP and UPPP, is that most OSA patients are inadequately treated on the basis of reduction in the RDI postoperatively [31]. The failure of LAUP in the treatment of OSA has been attributed to the limited resection of pharyngeal tissue compared with UPPP. Modification of the LAUP procedure to include a more complete resection of the pharynx was proposed by Mickelson and Ahuja [32], in which only 36 of 59 OSA patients (61%) underwent posttreatment polysomnography. These authors' conclusion that a more aggressive LAUP procedure is "an effective treatment for mild, moderate and severe OSA" is doubtful in view of the previously reported limited efficacy rate of UPPP and potential selection bias in the current study. The largest trial comparing pretreatment and posttreatment polysomnographic data in 58 LAUP patients showed a worsened posttreatment RDI in mild or moderate OSA patients and the persistence of severe OSA [33].

Somnoplasty is a novel palatal stiffening procedure performed on an outpatient basis. Palatal tissue is not excised or ablated as with UPPP or LAUP, but rather, a needle electrode is inserted near the border of the hard palate and directed toward the uvula. A generator delivers pulses of radiofrequency energy, which cause tissue necrosis and needle tract fibrosis over subsequent weeks to months. In this way a submucosal scar is created along the midline of the soft palate. The study by Powell and colleagues [34] demonstrated no major complications for this application of radiofrequency ablation to the soft palate in 22 patients. The authors also suggest an advantage of somnoplasty over LAUP or UPPP with respect to postoperative pain, which may be a result of the avoidance of mucosal transection; however, repetition of the procedure is usually required before the optimal surgical effect is obtained, which leads to increased cost.

The cautery-assisted palatal stiffening operation (CAPSO) is another outpatient mucosal surgery that induces a midline palatal scar to stiffen the floppy palate. Indications for CAPSO are habitual snoring and mild OSA. It has the advantage over radiofrequency ablation and LAUP that it avoids the need for multiple stage operations and does not rely on radiofrequency generators or expensive laser systems and hand pieces. CAPSO eliminates excessive snoring caused by palatal flutter and has success rates that are comparable with those of traditional palatal surgery [35]; however, according to Loube [31], postoperative pain is considerable and could preclude further study of this procedure.

Secondary skeletal procedures involving the chin

The surgical procedures that involve the chin aim at advancing the genial tubercles, which bear the insertions of the genioglossus muscles. These muscles are considered to be upper airway dilators that counteract the action of the pharyngeal constrictors and therefore are responsible for maintaining airway patency in the awakened state. Electromyography, however, has demonstrated marked depression of genioglossus activity, especially during the REM sleep, predisposing to upper airway obstruction in the retroglossal segment of the upper airway. The contribution of upper airway dilator muscle activity to the pathogenesis of OSA is now well recognized. The specifics of the GAHM procedure have already been mentioned. The alternative to the advancement of the genial tubercles is the advancement of the entire inferior border of the mandibular symphysis, which apart from the insertions of the genioglossus muscles also bears the insertions of the geniohyoid and the anterior bellies of the digastric muscles. This procedure is performed in exactly the same manner as a genioplasty, and the advanced segment is rigidly fixed in position with the help of prebent titanium advancement plates. The procedure has a cosmetic advantage in retrognathic individuals, and because the advanced segment has a bigger vascular pedicle through the lingual muscular insertions, fewer complications in terms of osseous necrosis and wound breakdown are expected with it.

Most patients referred for MMA have failed other forms of treatment or have not been compliant with home CPAP therapy and continue to suffer from fragmented sleep and excessive daytime somnolence. They usually have had upper airway reconstructive surgery in the form of UPPP with poor results. As a result, these patients are indicated for MMA surgery because this procedure is considered to be the best alternative to CPAP therapy, especially for obese patients refractory to other forms of treatment. Rarely, a patient presents without prior history of palatal surgery. Often he or she has a normal BMI; however, abnormal craniofacial morphology is demonstrated

Fig. 1. Standard dental models mounted on an articulator are used to fabricate a surgical advancement splint of the mandible (approximately 10 mm). Symmetric left and right movement with proper midlines and buccal overjet is important to reduce rotation.

clinically and cephalometrically (mandibular or maxillomandibular hypoplasia with narrowed posterior airway space at the level of the base of the tongue).

Tracheostomy is performed as a temporary measure in morbidly obese patients when control of the airway with conventional methods is problematic and risky. These patients are decannulated postoperatively when the concern of airway loss secondary to upper airway edema or hematoma ceases to exist. The genial tubercle advancement procedure has come into disfavor because of problems relating to postoperative infection, wound breakdown, or necrosis of the osteotomized and advanced segment. Furthermore, this procedure does not advance the digastric and geniohyoid muscles because their insertions are not included in the osteotomized segment. In our institution geniotomy advancement has replaced genial tubercle advancement as a less morbid and more effective procedure in regard to relieving retroglossal obstruction and suspending the hyoid bone in a more anterior and superior position. Midline glossectomy and nasal surgery (septoplasty, turbinectomy) are used as adjunctive procedures in selected patients with macroglossia and nasal obstruction, respectively.

Surgical technique of MMA

MMA surgery is performed with the following sequence of procedures: Initially bilateral sagittal split osteotomies mobilize the tooth-bearing portion of the mandible, which is advanced to the desired extent (usually 10 mm) and is temporarily held in this position with the help of a prefabricated advancement splint and maxillomandibular fixation with elastic bands, stainless steel wires, or both. A prefabricated acrylic occlusal splint is made on dental models and simple articulator to symmetrically advance the mandible (10 mm) (Fig.1). In this advanced position the mandibular osteotomies are rigidly fixed using bicor-

Fig. 2. Banked tibial bone is often used as an interpositional bone graft. It is perfectly cut to fit into the maxillary osteotomy and be rigidly fixed so as not to be displaced into the maxillary sinus.

tical positional screws. Two or three screws are required for rigid internal fixation on each side, and they are introduced in a perpendicular fashion to the bone surface with the help of stab incisions on the cheeks and a transbuccal trocar. The maxillomandibular fixation is then released, the intermediate advancement splint is removed, and the maxillary LeFort I osteotomy is performed. After maxillary downfracture and complete mobilization of the maxilla, the nasal septum and inferior turbinates are addressed. The maxillary segment is then advanced to the appropriate dental occlusion with the mandibular teeth, and in this position 2.0 prebent advancement plates are used for maxillary rigid internal fixation. A bone graft is mortised into the lateral wall of the maxilla and fixated into the advancement plate (Figs.2–4). The combination of these fixation plates with allogeneic cortical block grafts (eg, banked tibia) along the maxillary osteotomies is considered necessary to minimize the possibility of postoperative complications such as nonunion of the osteotomized segments or relapse secondary to stretching of the soft tissue drape after such extensive advancements. Surgery is concluded with the advancement geniotomy procedure for maximum results.

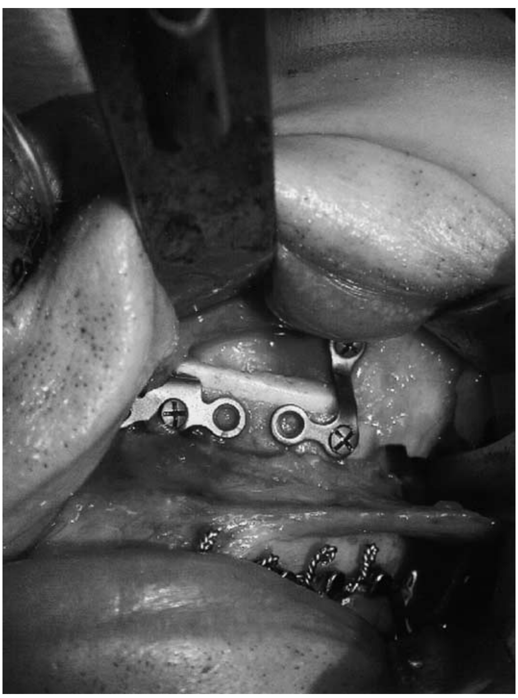

Fig. 3. The bone graft is mortised into the osteotomy gap after initial fixation. Note the bone is resting over the anterior plate and extending behind the maxilla. The two screws have not yet been secured into the graft.

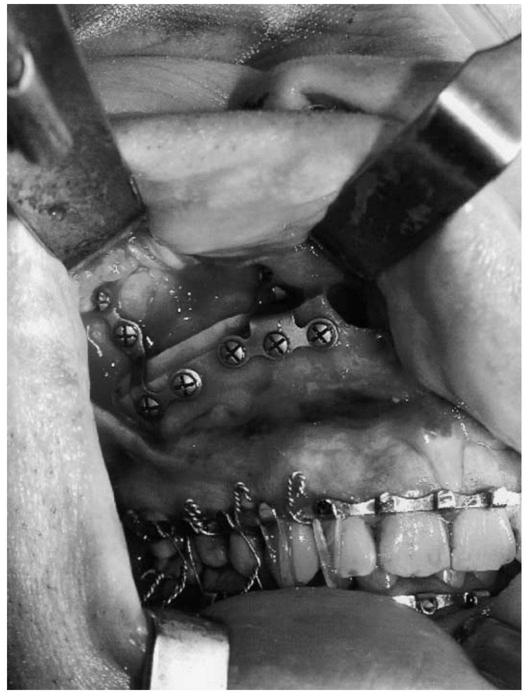

Fig. 4. The tibial bone graft is tapered like a wedge so that it will fit tightly into the osteotomy gap and then can be rigidly fixed into the maxillary plates.

Changes in upper airway dimensions and configuration after MMA as demonstrated with helical CT scanning

Seven adult OSA patients have undergone surgical treatment by MMA, and the results of preoperative and postoperative polysomnograms and preoperative and postoperative helical CT scans of the upper airway have been evaluated. A retrospective study evaluating the change in upper airway dimensions and configuration resulting from advancement of the maxillomandibular complex has been performed. The polysomnographic evaluation took place at least 2 months after the surgery. All patients had severe sleep apnea expressed as RDIs ranging from 47 events per hour to 134 events per hour (mean, 71.86 per hour). Their preoperative LSATs were recorded in the range of 55% to 88% (mean, 79%). The patients also underwent CT scanning of the upper airway with axial 5 mm cuts from the skull base down to the level of the trachea. All CT scans were obtained in the same radiology department of the University of Alabama at Birmingham by using third-generation helical CT scanners. The postoperative scans were obtained at least 2 months after the surgery.

For the scans the patients were placed in the gantry with the tragocanthal line perpendicular to the ground. Scanning times with the helical CT scanners were less than 15 seconds. The patients were instructed to breathe normally and to avoid swallowing during the scanning process. Flexible fiberoptic nasopharyngoscopy with Mueller's maneuver to identify sites of airway collapse with inspiratory effort and lateral cephalometric radiographs to identify abnormal craniofacial and upper airway soft tissue morphology were also included in the preoperative evaluation.

The patients were divided into two groups according to their response to MMA by using the postoperative polysomnographic data. In the group of the good responders were included patients who had >50% decrease of their preoperative RDI with the procedure. The patients who did not meet this criterion of success were included in the group of poor responders. The purpose was to correlate posterior airway space changes by CT scanning with polysomnogram results.

Acquisition of the data was performed with the help of an experienced radiology technician. The raw CT data saved in optical disk were retrieved. The preoperative and postoperative upper airway of each patient was studied starting at the level of the hard palate (level 0) and continuing caudally 10, 20, 30, 40, 50, 60, and 70 mm (levels 1 through 7, respectively) below that level until the body of the hyoid bone was visualized (Fig. 5). A set of three values was obtained at each airway level: (1) Anteroposterior (AP) dimension on the midsagittal plane (Fig.6); (2) maximum lateral dimension (LAT) in an orientation perpendicular to the midsagittal plane (Fig.7); and (3) cross-sectional area of the airway (CSA) (Fig.8). The measurement of the CSA was performed simply by following the perimeter of the airway with the cursor. No tracing or digitizing of the axial images was required (as in older CT studies) because the software available automatically calculated the

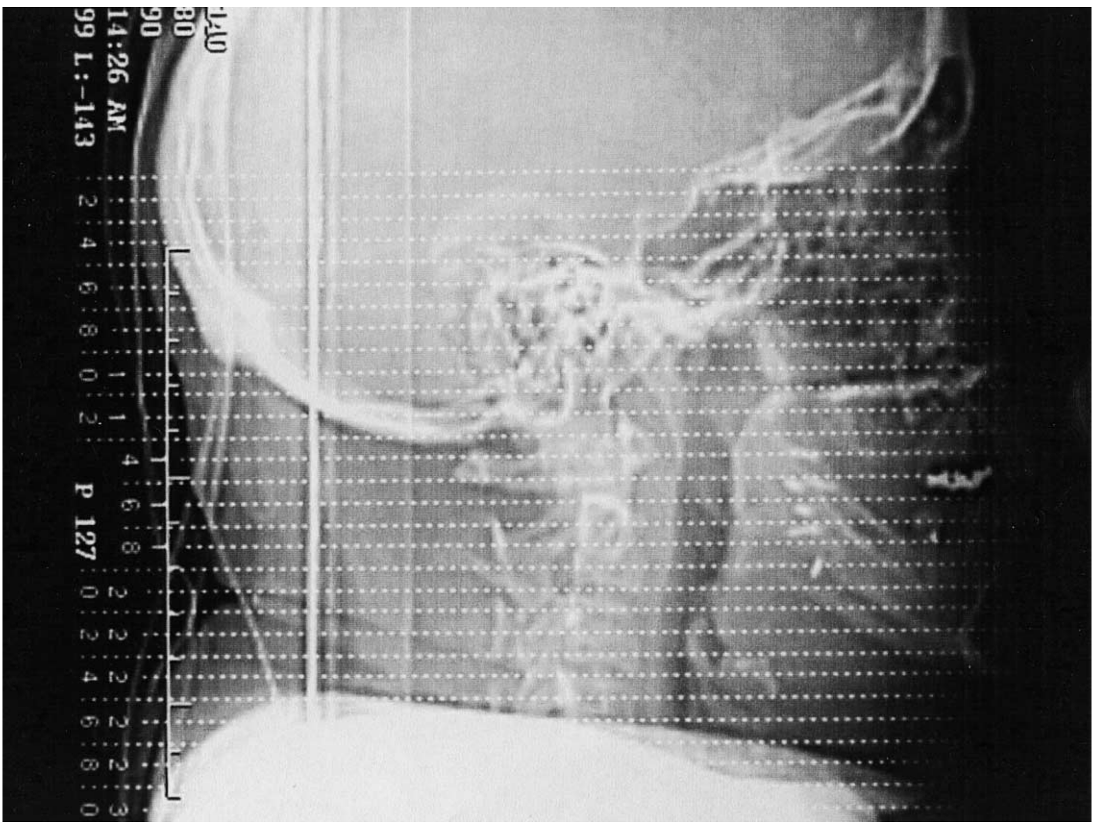

Fig. 5. Lateral neck scout view. Examination of the airway starts at the level of the hard palate and continues inferiorly down to the level of the hyoid bone in 5 mm axial cuts.

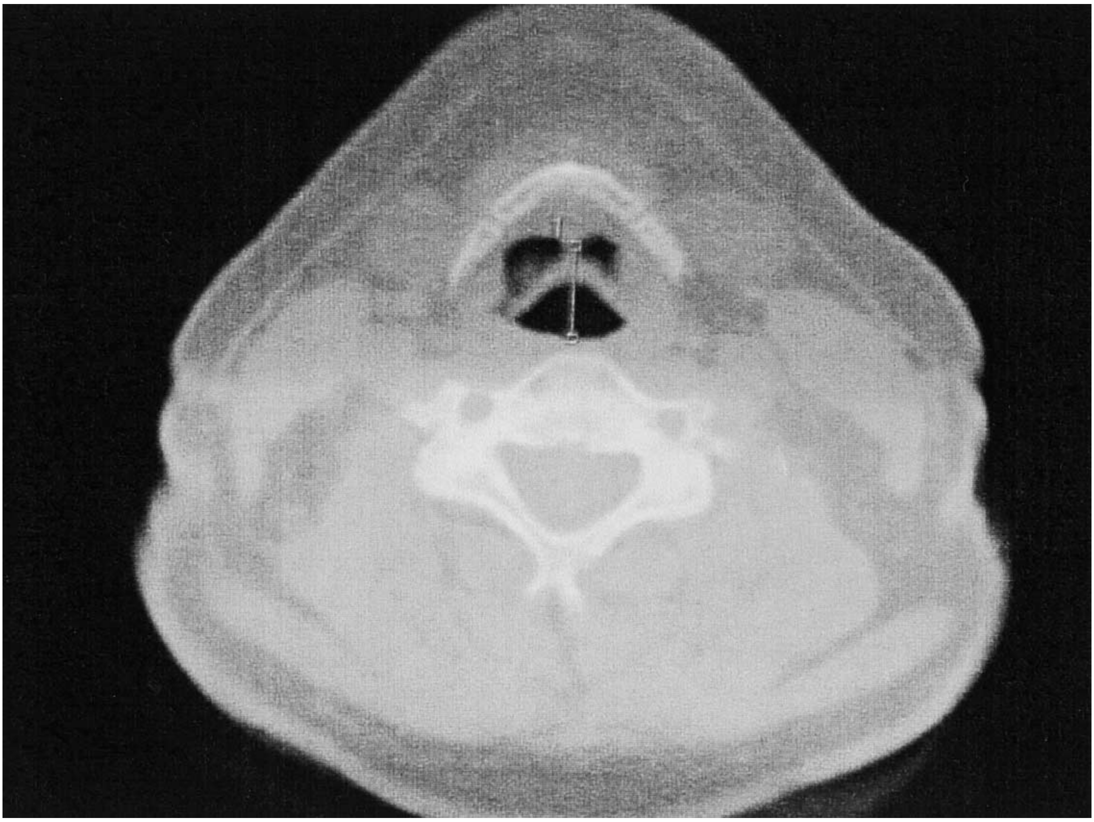

Fig. 6. Method for measurement of the AP dimension of the airway.

area contained within the scribbled line. We were also interested in measuring the amount of maxillary advancement.

Analysis of the results was performed using descriptive statistics (minimum, maximum, mean, and standard deviation). To calculate statistical significance in upper airway dimensional change resulting from MMA, the means procedure was used, which involved the application of a *t*-test. No statistical comparisons were attempted between the groups of the good and poor responders because the latter did not include an adequate number of subjects [36].

Demographic, anthropometric, preoperative, and postoperative polysomnographic data of the studied patient group are summarized in Tables 2 and 3. In the group of patients who had a good response to MMA (five out of seven), the mean preoperative RDI was 81 per hour and the mean postoperative RDI was 22 per hour. Overall, the group of the good responders experienced a mean decrease of 57 events per hour of sleep in their RDI.

In the group of patients with a poor response to MMA (two out of seven), the mean preoperative RDI was 53 per hour and the mean postoperative RDI was 45 per hour. One patient in this group experienced significant improvement in the RDI (from 51 per hour to 35 per hour) and an even more significant improvement in the LSAT (from 68% to 83%). The other patient of this group had the same postoperative RDI as preoperatively (55 per hour). Both of the poor responders were obese.

The mean preoperative and postoperative CT data of the AP and LAT of the upper airway demonstrated an increase at all levels. The mean airway CSA also increased at all levels after surgery. Statistically significant differences existed for levels at the hard palate and high retropalatal area.

This study also looked into the ratio of the LAT dimension to the AP dimension of the upper airway. At all levels the postoperative LAT/AP ratio was less than the preoperative, except for level 3 (high retroglossal area). At this level MMA stretched the airway in a more lateral than in AP fashion; however, the difference was not statistically significant for this level.

The quantitative effect of MMA on the LAT/AP dimension ratio at each level of the upper airway was

Fig. 7. Method for measurement of the LAT of the airway.

analyzed. The three patients who demonstrated the best result with a postoperative RDI of less than 20 events per hour appeared to have an airway that was stretched laterally at higher levels (hard palate and retropalatal area). At lower levels (retroglossal area and hypopharynx), their airway was stretched more in an AP fashion. Furthermore, the two patients who experienced >50% decrease in their RDI appeared to have a postoperative airway that demonstrated lateral stretching at more inferior levels compared to the previously mentioned group of patients with the best surgical result.

Discussion and conclusions

MMA increases both the AP and the LAT dimensions of the upper airway. The CSA was also increased in all levels.

Shepard and Thawley [12] studied the effect of UPPP on the upper airway by using CT. In this study UPPP increased upper airway caliber only at levels 1 and 2 (10 and 20 mm below the level of the hard palate, respectively) with statistical significance. At level 3 (30 mm below the level of the hard palate), there was a nonsignificant increase in upper airway CSA. In the retroglossal and hypopharyngeal areas (50, 60, and 70 mm below the level of the hard palate), however, the CSA of the airway was significantly smaller postoperatively than preoperatively [12].

MMA increases the CSA along the entire length of the airway by increasing both its AP and LAT dimensions. Skeletal advancement has a significant impact on the volume of the airway when described as a tube. Greater volume results in less resistance against the passage of air. Increase in airway caliber is not followed by proportionate decrease in resistance. The expected decrease in resistance is far greater than that because resistance is inversely proportional to the fourth power of the radius of the airway [26].

According to Prinsell, [29] MMA pulls forward the anterior pharyngeal tissues attached to the maxilla, mandible, and hyoid bone, thereby enlarging the entire velopharynx. The procedure is associated with minimal risks of edema-induced upper airway embarrassment or pharyngeal dysfunction.

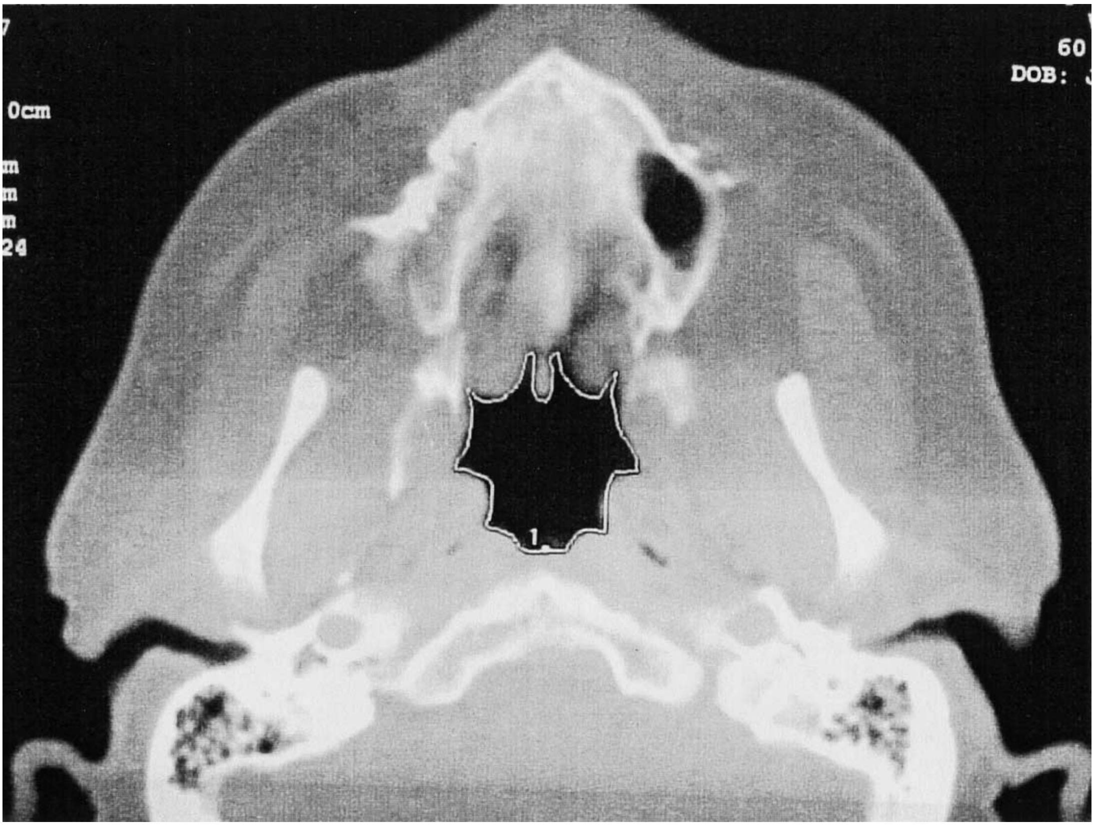

Fig. 8. Method for measurement of the CSA of the airway.

There should not be a concern that by advancing the maxillomandibular complex, the airway would be stretched merely in an AP fashion, bringing the lateral pharyngeal walls closer together toward the midline.

Table 2
Demographic, anthropometric, preoperative, and postoperative polysomnographic data of the patients with good response to maxillomandibular advancement

Patient	Age, race gender	BMI	Surgical history	Primary surgical procedure	Adjunctive surgical procedure	Date of surgery	Preop RDI	Preop LSAT	Postop RDI	Postop LSAT	Maxilla advance
TP	45 CF	55.04	None	MMA	None	11-Aug-00	134	88	15	83	11
PG	56 CF	16.46	Mandibular setback	MMA	None	26-Jul-00	47	87	5	89	11
DC	48 AAM	45.76	UPPP, septoplasty	MMA	Geniotomy adv., adenoids, turbinates	12-Jan-00	60	55	16	79	11
GC	57 CM	27.67	Tonsillectomy, nasal Sx	MMA	geniotomy adv.	08-Dec-99	100	87	47	78	10
WB	60 CM	27.65	UPPP, septoplasty	MMA	Turbinates	05-May-99	56	88	27	87	7
MEAN	53.2	34.52					79.4	81	22	83.2	10

Abbreviations: AAM, African-American male; BMI, body mass index (kg/m^2); CF, caucasion female; CM, caucasion male; LSAT, lowest hemoglobin oxygen saturation (%); maxilla advance, maxillary advancement (mm); RDI, respiratory distress index (events per hour of sleep).

Table 3
Demographic, anthropometric, preoperative, and postoperative polysomnographic data of the patients with poor response to maxillomandibular advancement

Patient	Age, race, gender	BMI	Surgical history	Primary surgical procedure	Adjunctive surgical procedure	Date of surgery	Preop RDI	Preop LSAT	Postop RDI	Postop LSAT	Maxilla advance
SE	38 CM	31.53	UPPP	MMA	Geniotomy adv., septum, turbinates	11-Oct-00	51	68	35	83	10
RJ	38 CM	31.69	UPPP, septoplasty	MMA	Turbinates	28-Apr-99	55	80	55	85	7
MEAN	38	31.61					53	74	45	84	8.5

Abbreviations: BMI, body mass index (kg/m^2); CM, Caucasian male; LSAT, lowest hemoglobin oxygen saturation (%); Maxilla advance, maxillary advancement (mm); RDI, respiratory distress index (events per hour of sleep).

This would place the airway at even greater risk of LAT collapse. Therefore, MMA resembles nasal CPAP, which acts as a pneumatic splint forcing the airway open by its continuous air column [37].

If, however, MMA enlarges the upper airway of sleep apneic patients with less resistance in airflow, then how can failure to respond be explained? A decrease in the postoperative LAT/AP ratio mathematically meant that the AP dimension of the airway increased or the LAT dimension decreased or both. It could also happen if both dimensions decreased; however, the LAT dimension should have decreased more than the AP dimension. The same result could also appear if both dimensions increased postoperatively; however, the AP dimension should have increased more than the LAT dimension. In any case, the net effect on the configuration of the airway would have been an AP stretching. In contrast, using the same logic as before, an increase in the postoperative LAT/AP ratio would result in a lateral stretch of the upper airway postoperatively.

In patients in whom a postoperative RDI <20 events per hour was achieved, the upper airway was stretched with MMA in a LAT orientation in higher levels (hard palate and retropalatal area); however, in lower levels (retroglossal area and hypopharynx), the upper airway was stretched more in an AP fashion. In patients in whom a poorer response to MMA was achieved, judging by a decrease in their RDI of at least 50%, the upper airway demonstrated this LAT stretching in more inferior levels compared to patients with the best result. Finally, the patient who did not respond to MMA at all, judging from equal preoperative and postoperative RDIs, demonstrated AP stretching of the upper airway at all levels, except the very last one in the hypopharyngeal area, where the stretching was evident more in the LAT orientation. It seems that LAT stretching has a high correlation with OSA improvement.

Success of upper airway surgery depends not only on enlargement of the CSA but also on the shape of the airway. Increase in the LAT dimension appeared to be of far greater importance than increase in the AP dimension. This observation is in agreement with conclusions made by Schwab et al [9] and Leiter [38].

Patients with poor response to MMA often have had a UPPP. It is possible that in these patients the failure of the airway to stretch laterally in the crucial retropalatal area may have been caused by scarring, making the tissues of the lateral pharyngeal walls stiffer and thus less responsive to advancement. Experience with cleft palate and UPPP patients shows that full mobilization of the maxilla becomes problematic when the soft palatal pedicle is scarred from previous surgical procedures. It is interesting to note that in this series of patients, the one with the most spectacular response to MMA (preoperative RDI of 134 per hour improving to a postoperative RDI of 15 per hour) did not undergo adjunctive upper airway reconstructive procedures such as UPPP or sliding geniotomy advancement. In addition, this patient was morbidly obese, with the highest BMI (55.04 kg/m^2) in the entire group, and the preoperative lateral cephalometric radiograph did not reveal maxillomandibular hypoplasia. CT evaluation did show significant change in posterior airway space.

Kato et al [39] used oral appliances to advance the mandible of patients with sleep-disordered breathing in a stepwise fashion (2, 4, and 6 mm). Their study showed that there was a dose-dependent effect of mandibular advancement on pharyngeal mechanics and nocturnal oxygenation. A 20% improvement of the oxygen desaturation index (ODI: number of oxygen drops >4% from the baseline) and of the CT_{90} (percentage of time spent at arterial oxygen saturation $<90\%$) could be expected for each 2-mm advancement of the mandible. In their study ODI was significantly associated with the higher P_{CRIT} (airway luminal pressure below which airway collapse occurs) values, indicating that improvement of collapsibility of the passive pharynx, mainly at the velopharyngeal level, resulted in improvement of nocturnal oxygenation. When the application of oral devices reduced the P_{CRIT} below atmospheric pressure, ODI decreased to < 10 per hour. By contrast, ODI remained >10 per hour when the P_{CRIT} remained above atmospheric pressure even with oral appliances. The authors [39] concluded that anterior tongue displacement caused by mandibular (genial tubercle) advancement might decrease the external pressure to the soft palate produced by posterior movement of the tongue base (especially in the supine position). Alternatively, anterior tongue displacement might stiffen the velopharynx through the palatoglossal arch, which connects the tongue base to the lateral wall of the soft palate. Mandibular advancement significantly decreased the P_{CRIT} at the retroglossal and the retropalatal (velopharyngeal) area of the oropharynx. The fact that mandibular advancement affects airway anatomy higher up in the airway than expected has also been demonstrated earlier by Isono et al [40].

No attempt has been made yet to study passive pharyngeal mechanics before and after MMA as Isono et al [40] have done for oral appliances. In addition to the relief of anatomic obstruction with mandibular advancement and subsequent forward displacement of the tongue, collapsibility of the pharynx is improved by "stiffening" of the pharyngeal walls through the stretching of the palatoglossus muscle. With MMA, it is not only the tongue that is displaced forward; the soft palate is also advanced, and a second influence on pharyngeal wall mechanics can certainly be hypothesized through the palatopharyngeus muscle.

Future Ct or MRI studies are needed to compare the two currently most important surgical approaches for reconstruction of the sleep apneic airway: MMA and UPPP. There is definitively a place for both in our armamentarium; however, it appears that the indications for the former are more frequent than the ones for the latter. It would be very useful but also ambitious to compare the two procedures to nasal CPAP therapy on weight-matched subjects in a prospective randomized fashion.

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