

Cephalometric Analysis and Long-Term Outcomes of Surgical Jaw
Advancement in Obstructive Sleep Apnea

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Abstract

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Purpose: To describe the posterior airway space and soft tissue changes in patients who received orthodontics and single or dual surgical jaw advancement and to evaluate if there is a correlation between increasing amounts of advancement and long-term reduction in obstructive sleep apnea.

Methods: Records were searched from one oral surgeon and one orthodontist for all patients treated by bilateral sagittal split osteotomy (BSSO) or maxillomandibular advancement (MMA) done in combination with orthodontics. Cephalometric films from pre-treatment, pre-surgery, post-surgery, and final removal of appliances were collected and traced. Pre-surgical and Post-surgical polysomnography results were collected, specifically the apnea-hypopnea indexes (AHI). The patients were recruited to complete a questionnaire and Epworth Sleepiness Scale (ESS) to assess long-term outcomes from treatment. Descriptive statistics were calculated for all cephalometric measurements and the data was analyzed for change from initial to final measurements with significance level set at $P < .05$. Linear regressions were performed to find estimates for the final OSA outcomes (AHI and ESS) as a function of mandibular advancement.

Results: Forty-three patients, treated from 1995-2010, were identified for the study. Twenty-nine patients had a complete cephalometric film series. The maxilla and mandible were advanced 5.2 mm and 8.3 mm respectively, with a mean 4 mm increase in posterior airway space. The upper and lower lip protrusion increased by 4.8 mm and 7.6 mm but there was no significant change in relation to the nose-chin line. The soft tissue chin increased by 11.3 mm. Thirty-three patients completed the long-term survey at a mean 6.3 years \pm 2.6 (range 2-12 years) after removal of appliances. The majority of patients (90%) reported reduction of their OSA symptoms and were pleased with their facial appearance. 79% of patients would recommend the orthodontic and surgical management of OSA to prospective candidates. 22 patients had initial AHI and final ESS values to assess final ESS score as a function of mandibular advancement. The mandibular advancement regression coefficient was -0.03 statistically and clinically insignificant. Twelve patients had initial and final AHI values to assess final AHI value as a function of mandibular advancement. The regression coefficient of mandibular advancement was 0.05, also statistically and clinically insignificant. No correlation could be found due to the lack of variation of mandibular advancement and limited sample size.

Conclusions: Soft tissue profile characteristics, AP airway dimensions, and skeletal maxillomandibular advancement were significantly increased after MMA. Soft tissue parameters were considerably protrusive but still demonstrate facial harmony. There was no evidence of a linear relationship between greater amounts of mandibular advancement and improvement of OSA outcomes. An advancement threshold could not be evaluated due to the limited sample size. Patients well below the recommended 10 mm advancement had successful objective short-term and subjective long-term reduction in OSA symptoms. Overall, patients were satisfied with their OSA management, facial aesthetics, and would recommend the treatment to others.

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DEDICATION to Mr. Chung, Mom and Dad

Introduction:

Obstructive sleep apnea (OSA) is a life-threatening condition presented as an inhibition or cessation of airflow during sleep, in conjunction with daytime sleepiness.¹ A sleep study or polysomnography (PSG) is required to diagnose OSA, along with daytime physical complaints. OSA is defined by the occurrence of 5 or more episodes of a 50% reduction (hypopnea) or cessation (apnea) of breathing for 10 or more seconds per hour of sleep (Apnea Hypopnea Index; AHI), with larger AHI values demonstrating increased severity.^{2,3} These apneic episodes are associated with repetitive sleep arousals and decreased blood oxygen saturation below 90%, resulting in significant risks for cardiovascular and cerebrovascular morbidity.^{4,5}

The etiology of OSA is complex and multifactorial. The inability to maintain upper airway patency during sleep develops due to a combination of anatomical obstructions in the oropharynx and nasal passages, impaired neuromuscular function and tone, or invagination of pharyngeal walls.⁶ Males, increasing age, obesity, African ethnicity and craniofacial features such as mandibular retrognathia are major risk factors for OSA.⁷⁻⁹ Anatomically, OSA subjects present with mandibular deficiency, bimaxillary retrusion, reduced cranial base length, increased lower facial height, elongated soft palate, large base of the tongue, and inferior position of the hyoid bone.¹⁰⁻¹³ Considering these varied associations, the correction of OSA can be difficult to achieve, and often necessitates several therapies.

Minimally invasive therapeutic options include lifestyle changes, oral appliances (OA), and continuous positive airway pressure (CPAP). Patients are often recommended diet and exercise interventions, due to OSA's relationship with obesity. A recent systematic review and meta-analysis reported that weight loss and increased physical activity reduced the AHI values and severity of OSA; however, these interventions alone did not normalize OSA parameters.¹⁴ OA are often prescribed to patients as a primary therapy for mild OSA and an alternative to CPAP. This device advances the mandible and tongue during sleep, thus increasing the upper airway volume. The 2006 Cochrane review suggested that OA improves subjective daytime sleepiness and AHI, but is less effective compared to CPAP.¹⁵ In addition, the device can be titrated beyond the normal limits of mandibular posturing and the reported side effects include discomfort in the

temporomandibular joint, mouth, and teeth, as well as bite changes and dry mouth.¹⁶

CPAP prevails as the first-line therapy recommended by clinicians for moderate to severe OSA.¹⁷ By delivering titrated airway pressure to maintain airway patency, CPAP reduces excessive daytime sleepiness and decreases cardiopulmonary risks.¹⁸ Unfortunately, patient discomfort and adverse affects associated with the device cause limited or part-time use, which promotes unrealistic, long-term compliance expectations.¹⁹⁻²¹ Due to poor patient CPAP adherence, physicians and patients sought alternative surgical therapies, which provide a more permanent correction.

Historically, tracheostomy was the first surgical treatment described for obstructive sleep apnea²²; however, the high rate of success was associated with numerous complications for the patient.²³ Uvulopalatoplasty (UPP), the standard treatment for moderate OSA, modified the airway by surgically removing obstructing airway tissues such as the uvula, soft palate, or enlarged tonsils. Fujita first reported a significant reduction in snoring, with long-term studies showing a success rate of 50% improvement in OSA symptoms.^{24,25} However, further studies revealed its lack of predictable success and associated side-effects with difficulty swallowing/nasal regurgitation, taste disturbances, and voice changes.²⁶⁻²⁸ Patients with reduced pharyngeal airway space, unfavorable position of the base of the tongue, or severe obesity had especially poor post-surgical outcomes.^{29,30}

The focus then shifted to multi-phase, multi-level surgery, which was first described by Riley and colleagues. Phase I surgery involved uvulopalatoplasty(UPPP) and/or genioglossus advancement and hyoid myotomy (GAHM), with 67% of the patients reporting success in reduction of OSA symptoms.³¹ This group had defined a “surgical success” as a 50% reduction of pre-operative respiratory disturbance index (RDI) and a “surgical cure” as a post-operative RDI<20. If patients were within these parameters, had minimal desaturations below 90%, and reduction in daytime sleepiness, they were considered “cured.”³² Patients with persistent, severe OSA, maxillomandibular deficiency, or morbid obesity with unresolved symptoms continued to Phase II surgery.³² The surgical protocol involved mandibular osteotomy with GAHM or the more aggressive, maxillomandibular advancement (MMA). By advancing the anterior pharyngeal tissues such as the soft palate, tongue base, and suprahyoid musculature, in

addition to the hyoid and base of tongue, MMO had shown a successful increase in posterior airway space (PAS) and significant improvement in sleep events and symptoms.³³⁻³⁵ Riley reported 97% surgical success rate for patients that completed Phase II surgery.³¹ Further studies yielded similar success rates,³³⁻³⁵ and MMA soon became the primary procedure for severe OSA, possessing the highest surgical efficacy comparable to CPAP therapy.^{36,10}

The surgical management of OSA has evolved over the last decade. Orthodontics is commonly used throughout treatment for coordination and stabilization, and many clinicians have adopted new guidelines for advancement. A systematic review in 2010 recommended larger MMA for more predictable surgical success,³ a concept based on the initial findings of Riley and colleagues in 2000. In this landmark study, a positive correlation was found with the amount of advancement and clinical improvement based on polysomnography results.³⁷ The study reported a clinically significant difference in the amount of advancement when separating patients based on improvement in RDI, and the authors concluded that 10 mm of advancement should be considered the surgical standard.^{32,37}

This 10 mm value has become the gold standard and the minimum amount of mandibular advancement that providers should strive to achieve in patients with OSA. However, this value is based on one relatively small study with several weaknesses. One weakness was that patients did not undergo orthodontic treatment in conjunction with the surgical procedures, possibly reducing the long-term stability. The findings of a “10 mm” cutoff threshold are based on the post-operative apnea severity, with greater mandibular advancement resulting in less apnea. However, the standard deviations are large, and the data were not adjusted for possible confounders, nor were they long-term. The study failed to find a statistical difference in the amount of surgical advancement and long-term successful treatment of apnea. Furthermore, the “surgical success” was defined as a 50% reduction in RDI and “surgical cure” as post-operative RDI<20. According to the American Academy of Sleep Medicine, OSA severity is categorized as mild for RDI ≥ 5 and <15, moderate for RDI ≥ 15 and >30, and severe as RDI >31.³⁸ RDI<20 can still be defined as moderate OSA, and patients with severe pre-operative values can still have unresolved symptoms with a 50% reduction in pre-operative RDI.

The RDI<20 limit may seem arbitrary, and more stringent post-operative RDI cutoffs could have affected the reported “success” and correlation. It is therefore doubtful whether there is a true 10 mm minimum advancement required for successful long-term treatment of apnea.

The correlation between the amounts of surgical advancement and long-term reduction of sleep apnea remains unclear. Clinical studies have shown reduction of AHI scores in the short-term follow up of 6-9 months, but long-term clinical results are unknown. In a recent cohort study with an 8-year follow up, patients who underwent 8 mm of MMA showed significant, stable reduction of AHI. The improvements of OSA symptoms were achieved without the preferred 10 cm advancement. However, the study had a small sample.³⁹ Due to anatomic limitations during surgery, some patients cannot undergo a large amount of advancement yet still achieve adequate oropharyngeal opening and improvement. Further studies are needed to investigate the relationship with the amount of advancement and long-term outcomes.

The primary aim of MMA is to increase the posterior airway volume, and clinicians are often concerned about the excessive protrusion and undesired esthetic change that patients experience with large advancements.⁴⁰ Li surveyed patients that were initially cephalometrically “normal” and were finished to “excessive maxillomandibular protrusion.” 96% of the patients were aware of the facial changes and 55% were pleased with the results.⁴⁰ The high surgical success rate in this selected sample may also cause a bias, for patients are likely to be satisfied with all other treatment results. A case series in 2009, which surveyed OSA patients and families, reported all individuals noticed facial appearance changes post-surgically and 52% of the patients were satisfied with the facial result.⁴¹ Facial changes, specifically soft tissue characteristics, have not been adequately described in OSA patients. Investigating the soft tissue changes that occur throughout treatment and assessing the patient’s response is important for both the clinician and patient for OSA management.

The purpose of this study is to describe the posterior airway space and soft tissue changes in patients that received orthodontics and single or dual surgical jaw advancement and to evaluate if there is a correlation between increasing amounts of advancement and long-term reduction in obstructive sleep apnea.

Materials and Methods

The orthognathic surgical records of one oral surgeon and of one orthodontist from 1995-2010 were searched for all obstructive sleep apnea patients treated (independent of outcome) with orthodontics and surgical jaw advancement. A sleep apnea diagnosis code in the electronic health record identified prospective patients in the study. Once patients were identified, an attempt was made to collect the cephalometric films from the oral surgeon and/or orthodontist that have overseen the completed treatment. Human subject approval for this study was obtained from the Institution Human Subjects Divisions.

The following inclusion and exclusion criteria were used:

Inclusion criteria:

- 1) Diagnosis of obstructive sleep apnea prior to orthodontic treatment as diagnosed by initial sleep study results: Respiratory Disturbance Index (RDI) > 20 or Apnea-Hypopnea Index (AHI) > 20.

- 2) Patients treated with orthodontics in conjunction with BSSO advancement or maxillomandibular advancement osteotomies; surgical advancement to verified by composite overlay of T2- T3

- 3) Cephalometric films available from each of the four timepoints:
T1= Initial/Pre-orthodontic film
T2= Pre-surgical film
T3= Post-surgical film
T4= Appliance removal/End of active orthodontics film

Exclusion criteria:

- 1) Incomplete, illegible, or non-diagnostic radiographs
- 2) Pre-treatment history of facial trauma, facial surgery, or any syndrome affecting the face

Study identification numbers for each cephalometric film replaced all patient identification information. All conventional cephalometric films were scanned with an Epson Expression 1680 scanner (Long Beach, CA) at 200 dpi and captured into Dolphin Imaging Software[®] Version 11.0 (Chatsworth, CA) for measurement. When digital films or images taken on the 3dMD™ system (Atlanta, GA) were available, they were captured and converted into a two-dimensional lateral cephalogram for consistency.

All cephalometric radiographs were digitized and traced by the same examiner. The examiner was blinded to the subjects' identity; however, The presence of malocclusion, appliances, and fixation allowed the examiner tracing the film to know the temporal sequence of the T1, T2, T3, and T4 films. The following orthodontic and skeletal landmarks were identified: Sella (S), Nasion (N), Porion (Po), Orbitale (Or), Posterior Nasal Spine (PNS), A-point (A), B-point (B), Gonion (Go), maxillary incisor tip (U1T), maxillary molar mesiobuccal cusp tip (Mx MBT), mandibular incisor tip(L1T), mandibular molar mesiobuccal cusp tip (Mn MBT), soft tissue Nasion(STN), nasal tip(NT), Subnasale(Sn), columella(Col), upper lip (UL), lower lip(LL), soft tissue Pogonion(STPog). (Figure 1)

The following reference lines were made on all tracings in order to create the descriptive linear and angular measurements of interest (Figure 2):

Direct reference lines:

- Esthetic plane (E-line) - joining the most anterior portion of the soft tissue nose (tip of nose) to the soft tissue chin (soft tissue Pogonion)
- Soft tissue Nasion perpendicular- constructed vertical at soft tissue Nasion to constructed horizontal plane (S'N -7°); serves as vertical reference for horizontal soft tissue millimeter measurements
- X- axis – constructed vertical at Sella and perpendicular to constructed horizontal plane; serves as a vertical reference for horizontal millimeter skeletal measurements (Figure 3)

Indirect reference lines

- S'N - 7° (constructed horizontal plane) - surrogate Frankfort horizontal plane

made by adding a correction factor of 7° to the Sella-Nasion line

The descriptive linear and angular cephalometric film measurements made at each time interval include:

Airway and dental movement (Figure 4):

- Overjet (OJ) - millimeter distance between two lines drawn from maxillary incisor edge and mandibular incisor edge perpendicular to the maxillary occlusal plane
- Posterior Airway Space (PAS) - millimeter distance between the base of the tongue and the posterior pharyngeal wall. Derived from a line connecting B-point to Gonion that extends through the base of the tongue to the posterior pharyngeal wall.

Horizontal/angular soft tissue nasal movement (Figure 5):

- Nasolabial angle (NL)- angular measurement from the columella, Subnasale, and upper lip
- Nasal tip projection (NProj)- millimeter distance of nasal tip to the vertical line constructed from Nasion perpendicular

Horizontal/AP soft tissue upper and lower lip movement (Figure 2):

- Upper lip to E plane (UL-E line): millimeter distance from upper lip protrusion (UL) to the E-line
- Lower Lip to E line (LL-E line): millimeter distance from lower lip protrusion (LL) to the E-line
- Upper lip to soft tissue Nasion perpendicular (UL-STNPerp) - millimeter distance from upper lip protrusion (UL) to soft tissue Nasion perpendicular line
- Lower lip to soft tissue Nasion perpendicular(LL-STNPerp) - millimeter distance from lower lip protrusion (LL) to soft tissue Nasion perpendicular line

Horizontal/angular soft tissue chin movement (Figure 6):

- Merifield's Z angle - angular measurement that joins the line tangent to the soft tissue chin (Pogonion) to the most anterior point of either the lower or upper lip (most protrusive lip); Perpendicular to Frankfort horizontal and serves as a reference for soft tissue chin prominence

- 0-degree meridian- millimeter distance of soft tissue Pogonion referenced from soft tissue Nasion perpendicular

Horizontal/AP Maxilla and/or Mandibular movement (Figure 3):

- X-axis to PNS (PNSx): millimeter distance from constructed vertical to the PNS; describes the horizontal position of the maxilla
- X-axis to B-point (Bx): millimeter distance from the constructed vertical to the B-point; describes the horizontal position of the mandible

To measure the skeletal and soft tissue changes throughout treatment, the difference was calculated for each of the descriptive measurements of PAS, PNSx, and Bx. The differences were created for each of the time periods: T1-T2, T2-T3, T3-T4, and T1-T4. The measured changes from T2-T3 verified the surgical advancement of the maxilla and/or mandible. The changes from T3-T4 demonstrated any post-surgical potential relapse and dentoalveolar corrections or compensations. The changes from T1-T4 demonstrated the overall skeletal and soft tissues changes throughout treatment.

All linear measurements were corrected for magnification. Cephalometric films possessing rulers or some magnification scale were adjusted accordingly. For films not possessing rulers, magnification was adjusted by using the millimetric length of the Sella-Nasion line and calibrated in Dolphin, as cranial base is considered relatively stable beyond 7 years of age.⁴²

Survey:

All patients identified for the retrospective cephalometric study were recruited to participate in an online survey (Figure 7). The survey assessed the long-term results of the obstructive sleep apnea treatment. Contact information was collected during the initial screening of records, along with the age, height, weight, gender, pretreatment start date, date of surgery, date of fixed orthodontic appliance removal, Angle classification, and initial and final polysomnography reports. A master list was created that linked the patients' profile to the identification numbers on the cephalometric films. This

information was used to compare the patients' long-term outcomes to the surgical and orthodontic treatment.

Patients who were successfully contacted by phone were invited to participate in the survey, which contained questions regarding the satisfaction with treatment, any further treatment sought, current weight and exercise habits, resolution of OSA symptoms, and the Epworth Sleepiness Scale (ESS), a standard, subjective questionnaire that assesses daytime sleepiness. Patients were emailed the link to the SurveyMonkey® (Palo Alto, CA) website where they could access the obstructive sleep apnea survey. Up to two reminder emails were sent at one-week intervals, if the patient did not complete the survey. Once an on-line consent was obtained and the survey completed, patients were compensated with a \$20 gift certificate to an online retailer.

Statistical Analysis:

Data collection and statistical analysis was completed using Microsoft Excel (Microsoft, Redmond, WA) and the Statistical Package for Social Sciences, version 19 (SPSS, Chicago, IL). Descriptive statistics were calculated for all cephalometric measurements, and the significance level was set at $P < .05$ for change from initial to final measurements. Linear regressions were performed to find estimates for the final OSA outcomes (AHI and ESS) as a function of mandibular advancement.

Errors due to landmark identification, tracing, digitization, and measurement were assessed by randomly choosing 4 patients (16 films), for the 16 linear and angular cephalometric parameters. These values are displayed in Table 1. Measurement error was assessed with Dahlberg's formula: $S^2 = \sum d^2 / 2N$, where d is the difference between repeated measurements and N is the sample size that was re-measured.⁴³ The highest method error was calculated to be 1.7 for the PAS and the lowest error was 0.1mm for UL-E line and UL-STN. Both values were considered acceptable.

Results:

Forty-three patients who were treated with mandibular or dual jaw advancement in conjunction with pre-surgical and post-surgical orthodontics for their obstructive sleep apnea were identified in the surgical and orthodontic records. Table 2 describes the initial

presentation of the total sample from the screening of records and sub-samples. The cephalometric sub-sample consisted of twenty-nine patients who had complete cephalometric films from initial to final treatment. The survey sub-sample consisted of thirty-three patients who participated in the long-term outcomes questionnaire and ESS evaluation. The ESS sub-sample consisted of twenty-two patients from the original thirty-three, who had complete cephalometric films, initial AHI values, and long-term ESS scores. The AHI sub-sample consisted of twelve patients who had complete cephalometric films and initial and final AHI values.

Twenty-nine patients fit the inclusion criteria for the cephalometric study. The main reason for exclusion was the lack of complete films at the four timepoints, most specifically the long-term film. Table 2 outlines the initial presentation of the cephalometric sub-sample. This sample had a balanced distribution of 15 men and 14 women, with an average age of 44.9 ± 9.3 years. The average body mass index (BMI) was $28.3 \pm 6.5 \text{ kg/m}^2$, categorizing the patients as overweight. The average AHI was severe at 48.6 ± 23.7 events/hour and the LSAT was $82.0 \pm 6.8\%$, which are values expected to qualify patients for the surgical management of obstructive sleep apnea. There were 6 patients with a skeletal CI I relationship, 19 patients with a CI II skeletal relationship, and 4 patients with a CI III relationship. 27 patients had MMA, while the remaining 2 had a mandibular advancement only. The average time from end of surgery to completion of treatment was 13.0 ± 8.1 months. The overall average treatment time from placement of orthodontic appliances to removal was 31.5 ± 11.8 months.

Compared to normal cephalometric measures, the patient sub-sample I at T1 presented with a decreased SNB, increased OJ, increased NL angle, increased distance of UL and LL to E line and soft tissue nasion (STN) perpendicular, and a constricted PAS in the AP dimension. These observations were not statistically tested for the extent of deviation from the normal values. The additional soft tissue and skeletal measurements were within cephalometric ranges of normal.

Table 2 displays all the cephalometric medians from each of the four timepoints throughout surgical and orthodontic treatment. From initial presentation to pre-surgery there was an increase in lip projection. In reference to E-line, UL increased by 2.7 mm and LL by 1.6 mm. In reference to STN perpendicular, UL increased by 1.85 mm and LL

by 1.35 mm. Nasal projection, nasolabial angle, Z-angle, soft tissue Pogonion to soft tissue Nasion perpendicular, SNA, SNB were relatively unchanged.

From pre-surgery to post-surgery, the skeletal advancement was verified by overlaying the composite tracings and quantified by the difference in values from the x-axis reference line. The median maxillary advancement was 5.4 mm and mandibular advancement was 8.3 mm respectively. The associated increase in posterior airway space was 5.1 mm to 11.1 mm, a value well within the normal range of PAS. The angular measurements also increased for SNA by 3.2° and SNB by 5.15°. These skeletal advancements caused numerous changes in the soft tissue profile, specifically a decrease in nasal projection by 2.9 mm and increase nasolabial angle by 8.3°. The upper and lower lips were excessively protrusive and the soft tissue Pogonion was more prominent due to the mandibular advancement and accompanying genioplasty procedure.

From post-surgery to debond, there was minimal, insignificant clinical relapse in the maxilla, mandibular and posterior airway space (Figure 8). Despite the minor skeletal change, there was a large reduction in soft tissue prominence. The nasolabial angle decreased by 5°, while the nasal projection increased by 2.2 mm. The lips remained protrusive but had lessened compared to post-surgical position. The upper and lower lips to E-line decreased in prominence by 2.9 mm and 4.1 mm respectively. In reference to STN perpendicular, the upper lip decreased by 3.7mm and 5.8 mm. Lastly, the soft tissue Pogonion decreased by 1.8 mm and the Z-angle decreased by 6.79°.

From initial to final time points, the large skeletal changes caused many of the patients to have fuller soft tissue profiles, based on the cephalometric values. The maxilla was significantly advanced by of 5.2 mm (P=0.002) (Figure 9) and the mandible by 8.3 mm (P=0.025) (Figure 10). This amount of skeletal advancement achieved a significant PAS increase of 4 mm (P=0.0001)(Figure 11). The angular measurements of SNA and SNB were also significantly increased by 3.0° (P=0.009) (Figure 12) and 2.3°(P=0.007) (Figure 13) respectively. The final values of SNA (85.8°) and SNB (82°) were both above the normal range, resulting in a protrusive appearance. When focusing on lip changes in reference to STN perpendicular, they resulted in being quite full. The UL and LL increased significantly by 4.8 mm (P=0.021) (Figure 14) and 7.6 mm (P=0.032) (Figure 15); however, in relation to the changes in the nose and chin, there was no

significant change. The soft tissue chin became more prominent, which was initially quite deficient. STN to Pogonion increased by 11.3 mm (Figure 16), while Z-angle increased by 8.65°(Figure 17). Dentally, the overjet was not significantly changed (Figure 18). The remaining soft tissue measurements of nasolabial angle (Figure 19), nasal projection (Figure 20), UL to E-line(Figure 21), LL to E-line (Figure 22) had a large reduction in values from post-surgical to debond, resulting in insignificant overall change.

Forty-three patients were recruited for the online survey, with 33 patients who completed the survey. Compared to the original recruited sample of 43, sub-sample II had a similar distribution of men and women, with slightly higher average age of 45.7 ± 8.9 years. The average BMI value paralleled the initial sample but the AHI values were more severe at 47.8 ± 24.8 events/hour versus 44.9 ± 23.6 events/hour. The majority of patients had Class II skeletal discrepancy and all but one patient had MMA. The average maxillary and mandibular advancement was $4.5 \text{ mm} \pm 2.8 \text{ mm}$ and $7.1 \text{ mm} \pm 4.6 \text{ mm}$ respectively.

The responses to the long-term survey questions are summarized in Table 3. The average follow up post-surgery/debond was $6.3 \text{ years} \pm 2.6$ (range 2-12 years). 90.3% of patients reported an improvement in OSA symptoms after the surgical and orthodontic treatment. The majority of patients did not pursue any further treatment, but individuals who had unresolved symptoms tended to revert back to the use of CPAP. A majority of patients did have fluctuations in weight (Table 4). 78% of patients reported a change in weight after the surgery, with 46% patients experiencing an average increase of 15 lbs (range 5-40 lbs). 42% of patients had noted changes in exercise habits, with the majority decreasing their activity. Overall, patients were aware of the changes that resulted from the surgery, and 90% were esthetically pleased with their facial appearance. Considering the positive responses to a successful reduction of OSA symptoms and post-operative facial changes, 79% of patients were overall satisfied with treatment and would recommend this OSA management to prospective candidates.

The 33 subjects also completed the Epworth Sleepiness Scale, a questionnaire that evaluates daytime sleepiness. Patients rated specific scenarios on a scale of 0 – 3, 3 being the highest chance of dozing or sleeping, and the composite scores would determine if they suffered from excessive daytime sleepiness (EDS). EDS severity is categorized as

normal to mild for a score <10 , “sleepy” or moderate for a score ≤ 10 and >18 , and “very sleepy” or severe as a score ≥ 18 . The average long-term ESS score was 5.83, which was well within the normal category; however, the range was 0-12, with 2 patients qualifying as “very sleepy.”

ESS is the standard clinical questionnaire to assess subjective outcomes for OSA management. To investigate if a relationship exists between mandibular advancement and subjective OSA outcomes, linear regression models were performed for the final ESS as a function of mandibular advancement. The amount of advancement was calculated as the difference of Bx from T4 and T1. 22 patients from the original sample of 33 were included, with a majority of the patients excluded due to lack of the long-term film (T4) to assess mandibular advancement and/or the initial AHI to adjust for severity. The ESS sub-sample was similar to cephalometric sub-sample, except the ESS sub-sample presented with a slightly lower AHI of 40.2 ± 29.5 events/hour versus 47.8 ± 24.8 events/hour. The scatterplot of the data is presented in Figure 23 and shows no evident linear relationship between the two factors. The linear regression models are presented in Table 5. The first model, which examined final ESS as a function of mandibular advancement, had a coefficient of mandibular advancement of -0.01 . The second model adjusted for the initial severity to see if any change was noted. ESS values were not initially collected pre-surgically, so AHI values were used as the surrogate. Model 2 had a coefficient of mandibular advancement of -0.03 . Both coefficients suggested no evidence for a linear relationship between final ESS and the amount of mandibular advancement.

AHI is the standard polysomnography value to assess objective outcomes for OSA management. The same linear regression models were created to investigate if relationship exists between mandibular advancement and AHI values. Of the initial 43 patients recruited, the final PSG could only be obtained from 12 patients. The AHI sub-sample included 5 men and 7 women, with a lower BMI of 25.8 ± 3.3 kg/m² and lower average AHI was 39.1 events/hour when compared to the total 43 patients. 3 patients were Class I skeletal, 7 patients were Class II skeletal and there were no Class III patients. The majority of patients had maxillomandibular advancement, with an average maxillary and mandibular advancement of 4.6 mm ± 2.8 and 7.2 mm ± 3.3 respectively.

According to the initial guidelines of success by Riley in 2000, all patients had a final AHI < 20 events/hour and reduction by 50% or more, qualifying the treatment a “surgical success” and “surgically cured.” Figure 24 illustrates the changes from initial to final AHI values. The average change in AHI values was 33.3 events/hour, where the follow-up PSG was completed 6 months after surgery. The scatterplot of the data is presented in figure 25 and shows no evident linear relationship between the two factors. The linear regression models are presented in Table 6. Model 1 had a coefficient of mandibular advancement of 0.05, while model 2, which adjusted for initial AHI severity, had a coefficient of 0.06. Interestingly, there was no difference in values when adjusted for initial severity. Both coefficients suggested no evidence for a linear relationship between final AHI and the amount of mandibular advancement. Both values were found to be insignificant, which is expected due to the small, variable sample. Due to the lack of a distribution of mandibular advancements of 10 mm or more, a threshold value could also not be established in our sample.

Discussion:

When less invasive positive airway pressure devices are not well tolerated, patients with severe OSA are often treated by surgical correction, specifically BSSO or MMA. Larger advancements of 10 mm have had advocated for successful outcomes to normalize respiration and sleep in OSA patients. However, this degree of advancement carries with it major esthetic concerns and morbidity.³⁷ The soft tissue changes that occur throughout orthodontic and surgical treatment have not been clearly described in OSA patients. Due to anatomic limitations, some patients cannot undergo a large amount of advancement yet still achieve adequate oropharyngeal opening and improvement. The correlation between the amounts of surgical advancement and long-term reduction of sleep apnea remains unclear.

This sample of 29 patients initially presented as middle-aged (mean age 45 years old), overweight adults with severe OSA. When compared to cephalometric norms, they were noted to have mandibular retrognathia, increased overjet, retrusive upper and lower lips contributing to an increased nasolabial angle, and a constricted posterior airway space. These characteristics parallel the cephalometric findings previously reported in the

literature for obstructive sleep apnea patients.⁴⁴ Bimaxillary retrusion is a diagnosis, which suits the treatment protocol of dual jaw advancement; however, this sample was mostly comprised of Class II mandibular deficient patients. The cephalometric focus of the study was on soft tissue profile characteristics and PAS.

There was insignificant change in the maxilla, mandible and posterior airway space from post-surgery to final treatment. Although the average time from T3-T4 was 13 months, previous long-term studies have confirmed the stability of large skeletal advancements.^{45,46} However, Li *et al* conducted a study with the mean follow-up of 45.7 ± 29.6 months (12-132 months), where he observed a 34% relapse (10.1 mm to 6.7 mm) in the PAS. Posterior airway space may be more susceptible to relapse, possibly due to the dynamic tissues that comprise the airway. MMA is effective in the short-term improvement of PAS, but the long-term maintenance of PAS patency in MMA patients is unknown.

In this study, the amount of MMA advancement was personalized to the facial characteristics of each patient, and the skeletal bases were significantly advanced but not to the recommended 10 mm. From initial to final treatment, the maxilla and mandible were advanced by an average of 5.4 mm and 8.3 mm respectively. The PAS increased from 6.7 mm to 10.7 mm, which is within the normal PAS range of 11-12 mm. The main goal of MMA is to address the restriction of PAS, and the observed increase in AP airway dimension was statistically and clinically significant. Liu *et al* recently conducted a study in a smaller Chinese sample where 12 patients underwent 5–10 mm (mean 7.4 mm) of MMA advancement and had reported a similar statistically significant increase in PAS from 6.75 mm to 9.79 mm.⁴⁷ The amount of opening observed is similar to those achieved by studies advocating 10 mm or more of advancement. Visualizing the airway in the transverse dimension may better explain the effect of MMA on the oropharyngeal space. Patients with severe OSA have been found to have more constricted lateral airway dimensions than mild snorers and 244 controls.^{48,49} Fairburn reported CT evaluations with dramatic increases at all levels in the AP and lateral dimension in 20 consecutive patients treated by MMA.⁴⁸ The airway increase in the transverse versus AP direction may have more significance, and may not be dependent on maximizing the advancement.

Li and colleagues could not find a correlation with the amount of advancement and the AP posterior airway opening observed, but did report a significant correlation with the amount of mandibular advancement and postoperative polysomnographic outcomes.³² This >10 mm advancement of the maxillomandibular complex, yielded a 90-100% surgery “cure” rate in their study.³⁷ Their definition of success was in the lower tier of outcomes when compared to other studies. In a meta-analysis and systematic review involving 627 adults, Holty and Guilleminault defined “surgical success” as a final AHI<20 events/hour and reduction by 50% or more and “surgical cure” as AHI<5 events/hour. They reported a success and cure rate of $86.0 \pm 30.9\%$ and $43.2 \pm 11.7\%$ respectively, with a mean AHI decrease of 63.9 events/hour to 9.5 events/hour.³ According to these guidelines, this study had similar results, with 100% of patients with “surgical success” and 50% (6 of 12) of the sample “surgically cured.” These results should be noted with caution, for the sample size only consisted of 12 patients and the average AHI was severe at 39 events/hour, with high variance.

Holty and Guilleminault had still advocated larger MMA advancements for more predictable success. Their mean maxillary and mandibular advancement was 8.7mm and 10.7 mm, which was greater than the maxillary (mean 4.5 mm \pm 2.8) and mandibular advancement (mean 7.2 mm \pm 3.3) in this sample. A recent study by Giarda *et al* reported very similar MMA values to the Holty and Guilleminault study, specifically a maxillary advancement of 9.1 mm \pm 1.3 and a mandibular advancement of 8.9 mm \pm 1.3mm. Giarda reported a surgical success rate of 100% and a lower surgical cure rate was at 37.5%. These values were derived from the same “success guidelines” adapted by the review. Liu also reported on patients with an MMA advancement of 5-10 mm (average 7.4 mm), which was similar to the advancement noted in the sample. He had reported an 83% surgical success rate.⁴⁷ In 2012, Hseih and Liao conducted a systematic review where the studies observed maxillary and mandibular advancement ranges were 7.3 mm - 9.2 mm and 10.2 mm to 12.5 mm. Despite the larger range of advancements achieved, the surgical success still had a range of 65-100%.⁵⁰ Therefore, the concept of larger amounts of advancement leading to more predictable surgical success or cure is still debatable. Individuals can still have acceptable surgical success and cure rates without larger advancements. It is also important to note that definitions of surgical success or AHI

cutoffs can significantly modify the treatment effectiveness.

This study aimed to investigate the correlation of amounts of mandibular advancement and improvement in OSA outcomes through regression analysis. The model for AHI and mandibular advancement had a coefficient of 0.06 and 0.05 when adjusted for initial AHI severity. According to these values, adjusting for the initial severity did not significantly change the relationship between the two variables. The models suggest no correlation with increasing amounts of mandibular advancement and final AHI values. The results should be evaluated with caution, since the AHI values are short-term (6-9 months) rather than preferred long-term AHI (1 year or more). Lack of linear relationship could be explained by the limited sample size (12) and large variation.

A linear regression model was created to assess the subjective outcomes of OSA, specifically ESS with mandibular advancement. Due to the ease of collecting ESS scores, this was a convenient sample to assess long-term outcomes of OSA. The model for final ESS and mandibular advancement had a coefficient of -0.01 and -0.03 when adjusted for initial AHI severity. Initial ESS would have been a more appropriate value for adjustment, but due to the retrospective nature of the study these values were not available. Factoring the initial severity into the regression did not show a significant change in the coefficient. The models suggest no evidence of a correlation with larger amounts of advancement and lower final ESS scores. The importance of ESS outcomes for OSA patients remains unclear. ESS is a reliable measure of excessive daytime sleepiness (EDS) most often used in OSA outcome studies, but patients with OSA may not always present with EDS. The correlation of AHI and ESS is also variable. The presence of EDS in OSA patients has shown to have only a mild impact on respiratory disturbance: small increases in AHI values, and slightly lower oxygen desaturations.⁵¹ This may indicate that ESS and AHI may measure two different aspects of the disease, and are both important outcome measures.

This study found no evidence for a correlation with larger amounts of advancement and improvement in OSA outcomes. The 10 mm gold standard could not be addressed due to the limited distribution of the sample, with a majority of the patients completing 7-8 mm of advancement. Interestingly, Lye et al reported a statistically significant correlation with the amount of maxillary advancement and the reduction in

AHI;⁵² however, other studies reported no association between the two variables.⁵³ It is worth noting the patients in the study had high surgical success and cure rates, comparable to those reported in the literature.^{3,32} Individuals can still have acceptable OSA success without aiming for larger advancements.

A high positive response was observed for issues regarding reduction of OSA symptoms, facial esthetics, and overall satisfaction with treatment. 90% (30 of 33) of patients had experienced a reduction in OSA symptoms. Just the experience of undergoing a rigorous surgery may have also contributed to the reported improvement. The “surgical process” may explain why patients have reported reduction of OSA symptoms despite the large range of maxillomandibular advancements measured. The remaining 3 patients had reported issues with snoring and incomplete resolution of symptoms, specifically when sleeping supine. This indicates the OSA treatment efficacy may be dependent on sleep conditions, specifically orientation and position. Li et al reported the deleterious effects of extreme weight gain on long-term stability of surgical success. He noted that minor weight gain had minimal adverse effects, but severe amounts (40-50 lbs) caused reoccurrence of symptoms.³² 45.5% (18 of 33) of patients in this study reported an increase in weight gain, while 33.3% (11 of 33) experienced a decrease in weight. The average weight gain was 15 lbs, but the range of 5-40 lbs did include severe weight changes. Despite to fluctuation in weight, 57.6% (19 of 33) reported no change in exercise habits. As expected, 93.9 % patients did not seek additional surgery or therapy, but 19.4% of patients reported CPAP use. CPAP was the most common device used to address any lingering symptoms, with oral positioner appliances and even acupuncture as noted alternative therapies.

One of the main disadvantages of MMA is causing excessive skeletal and soft tissue protrusion. In this sample (29), a majority of the patients initially were Class II due to mandibular retrognathia (SNB=77.7°). MMA and genioplasty would help improve the discrepancy between the jaws and weak chin, but it would also advance the maxilla, which was in an acceptable position relative to cranial base (SNA=82.6°). This puts the patients at risk of excessive protrusion of the maxilla and superior lip. The final values for SNA and SNB were 85.6° and 82°, qualifying the patients as bimaxillary prognathic. Studies have noted the skeletal to soft tissue advancement 0.6-0.9 in the maxilla and

nearly 1 to 1 in the mandible.⁵⁴⁻⁵⁶ In this study, the upper lip increased by 4.8 mm and the lower lip by 7.8mm, which was statistically significant and bimaxillary protrusive. However, these values were based on absolute increases, and when examined in relationship to the E-line they were much less protrusive. The soft tissue Pogonion increased significantly by 11.3 mm, which was a favorable change in a retrognathic sample. Patients originally presented with a slightly increased nasolabial angle (107°), and were at risk to grossly accentuate the angle after the maxillary advancement. Interestingly, the upturned nasal tip was observed in a majority of the patients at T4, but the prominence of the upper lip limited the nasolabial angle change. Conley *et al* also reported on similar changes in MMA, such as minimal rotation of the nasal tip and a minor reduction in nasolabial angle.⁵⁴ These findings suggest that MMA largely modifies the soft tissue parameters, but the facial harmony between the nose, lips, and chin remains acceptable. This concept of facial harmony is supported by Czarnecki, who demonstrated that the presence of a large nose and/or chin balances larger lip protrusion.⁵⁷

Patient perception of long-term facial esthetics after MMA was mainly positive. There are several explanations for the high acceptance rate of the post-surgical facial esthetics. The maxillomandibular protrusion is more “forgiving” in an OSA population, whom are commonly overweight and of older age. Patients in their fourth decade of life experience the common signs of aging: nose to mouth folds, softened jawline, sagging neck and overall jowling or laxity of facial tissue.⁵⁸ MMA increases the facial soft-tissue support and improves definition, which are perceived as a more youthful, attractive appearance. Patients who are overweight often have excess soft tissue that can “mask” the underlying skeletal protrusion. The cephalometric changes of MMA were noted on profile in an AP dimension. Patients may rarely see themselves in profile view, where the changes may be most apparent. Lastly, patients are undergoing surgery to resolve their OSA symptoms, so their major focus is not on esthetic outcomes rather quality of life.

The literature also reports a generally positive acceptance of post-surgical facial esthetics. Li *et al* had surveyed patients 6-12 months post-surgery to assess patients’ perception of facial aesthetics and reported similar results. He found that 90% of patients had a positive or neutral response to the surgery, with 55% considering the changes

favorable.⁴⁰ In fact, a recent study by Lui *et al* had surveyed laypeople to score patients' profiles before and after MMA. Laypeople gave significantly higher scores to postoperative images, due to the rejuvenating, facelift effect.⁴⁷ In a case series of thirty-eight patients, 52.6% (20 of 38) were satisfied with esthetics, while 28.9% (11 of 38) were indifferent.⁴¹ Therefore, slightly more than half of OSA patients will be pleased with final aesthetics, but the majority will generally tolerate the protrusion associated with MMA, mainly due to the compensating "soft tissue drape of aging and obesity."⁴⁰

Li also recognized that some patients will view the changes as unfavorable, and these patients typically had a "thinner" soft tissue profile that could not mask the protrusion effectively. In this study, there was no assessment of the thickness of the soft tissue profile. Reasons for dissatisfaction with facial appearance varied. All patients noted the change as "different" while one described that his "jaw juts out too much." Individuals are fine with the change, not 100% pleased with the change, but are not so concerned to pursue any further cosmetic treatment. Furthermore, a patient commented that his spouse was more concerned than him about his facial appearance. This finding suggests it may be important to counsel family members and spouses on the cosmetic changes of MMA.

The overall satisfaction with treatment had the lowest positive response. 78.8% (26 of 33) of patients had improvement in their quality of life and would recommend it to others. Seven patients felt that the final results did not justify the means. Patients with incomplete resolution of symptoms were included in this group. Other patients had reported difficulty with the extensive recovery period involved with the surgery. Some patients attributed their dissatisfaction with the unfavorable changes in bite or appearance. Although 20% would not advocate the treatment, a majority of the patients saw the benefit of the MMA surgical and orthodontic management and a viable treatment option for OSA.

The findings of this study must be regarded with some caution as there are several limitations to retrospective cephalometric studies of this nature and potential for selection bias. Landmark identification was an inherent limitation in using cephalometric films, and especially when surgical procedures and rigid fixation may obscure and/or alter landmarks. It was often also difficult to discern between dental and skeletal changes

amongst moving parts. Head films from each office may not be standardized, but were calibrated accordingly with scanned rulers. The potential for magnification differences between serial films was possible, and were accounted for as best as possible, but could not be without error.

There were several limitations with evaluation of airway. The airway shape is variable and can be easily affected by head posture and breathing stage. Since cephalometric films are 2-dimensional, there are limitations to accurately identifying the transverse airway dimension and changes as a result of MMA. Furthermore, the head films are recorded with the patient in the upright resting position, which does not truly capture the anatomic position or obstruction during natural sleep conditions. A correlation between CT scans and cephalometry has been done, showing that some of the anatomic factors present during OSA will be present during waking conditions.⁵⁹ Previous studies have found good correlations between cephalometric and CT measurements for several pharyngeal structures such as the tongue, soft palate, and nasopharynx.^{60,61}

Surgical studies focus on AHI to validate treatment effectiveness. The ideal assessment of reduction in OSA is through analysis of pre-surgical versus post-surgical or long-term AHI values. Unfortunately, many patients failed to pursue the follow-up sleep study due to inconvenience, finances, or felt it unnecessary if their symptoms were resolved. The questionnaire is a surrogate assessment of subjective improvement and possesses inherent biases and inaccuracies. Patients may report more favorably to treatment because they are participating in a survey. The placebo effect of undergoing an extensive surgical treatment may cause patients to express an improvement in OSA symptoms. Patients who may use devices to help with residual OSA symptoms, have experienced weight gain, or had undergone further surgery may also bias the responses of the questionnaire and are definite confounders to the study. Therefore, it is difficult to assume the resolution of symptoms reported by a majority of the patients was due to the surgical therapy. Lastly, the AHI values and patient-centered outcomes are all proxies for the mortality rate, which is the true measure of treatment effectiveness for OSA.

In conclusion, the findings of this study indicate that soft tissue profile characteristics, AP airway dimensions, and skeletal maxillary and mandibular

advancement were significantly increased after MMA. Soft tissue parameters were considerably more protrusive, but well balanced in relationship to each other. Patients' perception of the final facial esthetics was positive, and generally well accepted as reported in the literature. There was no evidence for a correlation with larger amounts of mandibular advancement and improvement in OSA outcomes. A threshold could not be found for the amount of advancement and improvement of sleep apnea, due to the limited distribution of the sample. However, patients well below 10 mm had successful subjective and objective reductions in OSA symptoms. Overall, Patients were satisfied with the surgical and orthodontic management of their OSA, reported a reduction in sleep apnea symptoms, and would recommend the treatment to other

Conclusions:

The combination of orthodontic and surgical treatment in sleep apnea patients results in:

1. A significant increase in the soft tissue profile characteristics, AP airway dimensions, and skeletal maxillary and mandibular advancement. Soft tissue parameters are considerably protrusive, but well balanced in relationship to each other.
2. There was no evidence of a correlation between greater amounts of mandibular advancement and improvement of OSA outcomes.
3. A threshold could not be found for the amount of advancement and improvement of sleep apnea, due to the limited distribution of the sample. However, patients with surgical advancement well below 1 cm had successful subjective and objective long-term reduction in OSA symptoms.
4. Patients were overall satisfied with the surgical and orthodontic management of their OSA. A majority of patients reported a reduction in sleep apnea symptoms, satisfaction with facial aesthetics, and would recommend the treatment to others.

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Tables:

Table 1. Measurement error for the angular and linear cephalometric measurements.

Measurement Error	
SNA (deg)	0.7
SNB (deg)	1.0
OJ (mm)	0.4
NL (deg)	0.8
NProj (mm)	0.6
UL-E (mm)	0.1
LL-E (mm)	0.2
UL-STN (mm)	0.1
LL-STN (mm)	0.3
Pog-STN (mm)	0.2
Z angle (deg)	0.8
PAS (mm)	1.7
Bpt-X (mm)	0.8
PNS-X (mm)	0.6

Table 2. Patient data for the initial sample and sub-samples.

	Total Sample (N=43)	Ceph Sub-sample (N=29)	Survey Sub-sample (N=33)	ESS Sub-sample (N=22)	AHI Sub-sample (N=12)
Parameters	Average ± SD	Average ± SD	Average ± SD	Average ± SD	Average ± SD
Age (years)	44.9 ± 9.4	44.9 ± 9.3	45.7 ± 8.9	45.4 ± 9.0	43.6 ± 8.4
Men (%)	26 (60)	15 (52)	18 (55)	10 (45)	5 (42)
Women (%)	17 (40)	14 (48)	15 (45)	12 (55)	7 (58)
BMI (kg/m ²)	28.2 ± 5.6 ^a	28.3 ± 6.5 ^c	27.3 ± 4.0 ^e	26.6 ± 3.6	25.8 ± 3.3
AHI (events/hour)	44.9±23.6 ^a	48.6±23.7 ^c	47.8 ± 24.8 ^e	40.2 ± 29.5	39.1 ± 25.2
LSAT (%)	82.9 ± 6.9 ^b	82 ± 6.8 ^d	82.3 ± 7.3 ^f	83.3 ± 6.5	83.3 ± 6.4
MMA (%)	38 (88)	27 (93)	30 (91)	20 (91)	11 (92)
Mandibular Advancement (%)	5 (12)	2 (7)	3 (9)	2 (9)	1 (8)
Class I Skeletal (%)	8 (19)	6 (21)	6(25)	3(14)	2(17)
Class II Skeletal (%)	27 (63)	19 (66)	22(75)	17 (77)	10(83)
Class III Skeletal (%)	8 (19)	4 (13)	5 (0)	2 (9)	0 (0)

SD=standard deviation; BMI= body mass index; AHI=apnea-hypopnea index; LSAT= lowest oxygen saturation; MMA= maxillomandibular advancement; a= 29 subjects; b= 35 subjects; c= 19 subjects, d= 22 subjects; e= 23 subjects; f= 25 subjects; Ceph, AHI, ESS, and survey sub-samples as described in the results

Table 3. Long-term survey responses for OSA Management. Survey sub-sample (N=33)

	Yes	No
Did you have improvement in your OSA after the surgery and orthodontic treatment?	90.9% (30)	9.1% (3)
Did you seek any further surgery or treatment after the previous surgical procedure?	6.1% (2)	93.9% (31)
Are you currently using CPAP or another device to improve your OSA?	18.2% (6)	81.8% (25)
Are you pleased with your facial appearance after the surgery?	90.9% (30)	9.1% (3)
Would you recommend the surgical treatment to others?	78.8% (26)	21.2% (7)

Table 4: Long-term weight and exercise responses. Survey sub-sample II.(N=33)

	Yes Reduction	Yes Increase	No
Have you had a change in weight after surgery to present?	33.3% (11)	45.5% (15)	24.2% (8)
Have your exercise habits changed from surgery to present?	33.3% (11)	9.1% (3)	57.6% (19)

Table 5. Linear regression estimates for final ESS and mandibular advancement. ESS sub-sample (N=22)

Model	Description	Estimate	95% CI	P value
1	ESS final ~ ΔBpt	-0.03	-0.44 – 0.37	0.86
2	ESS final ~ ΔBpt+ AHI initial	-0.01	-0.40 – 0.38	0.97

AHI=apnea-hypopnea index; ΔBpt= mandibular advancement (T4-T1); CI= confidence interval; Estimate= coefficient of ΔBpt; ESS final~ΔBpt =final AHI as a function of mandibular advancement; ESS final~ΔBpt+ initial AHI=final AHI as a function of mandibular advancement, adjusted for initial AHI.

Table 6: Linear regression estimates for final AHI and mandibular advancement. AHI sub-sample (N=12)

Model	Description	Estimate	95% CI	P value
1	AHI.final~ΔBpt	0.06	-1.11- 1.23	0.91
2	AHI.final~ΔBpt+ initial AHI	0.05	-1.15-1.25	0.93

AHI=apnea-hypopnea index; ΔBpt= mandibular advancement (T4-T1); Estimate= coefficient of ΔBpt; CI= confidence interval; AHI final~ΔBpt =final AHI as a function of mandibular advancement; AHI final~ΔBpt+ initial AHI=final AHI as a function of mandibular advancement, adjusted for initial AHI

Figures:

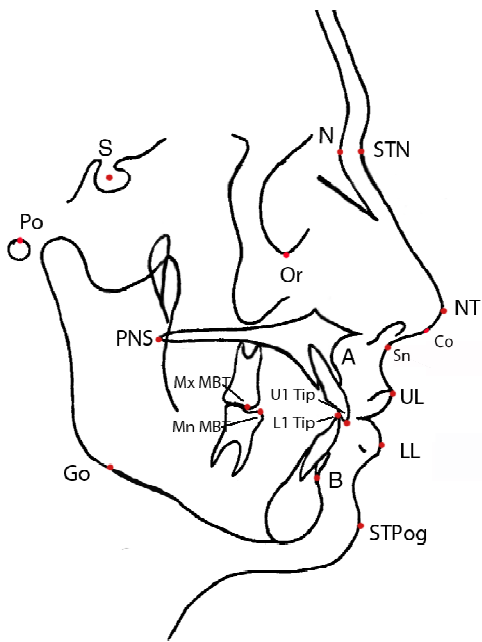


Figure 1. Soft tissue and skeletal measurement landmarks.

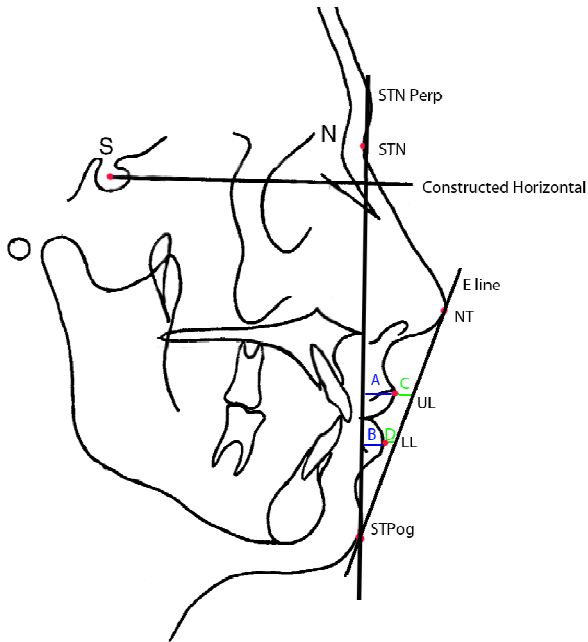


Figure 2. Soft tissue lip measurements

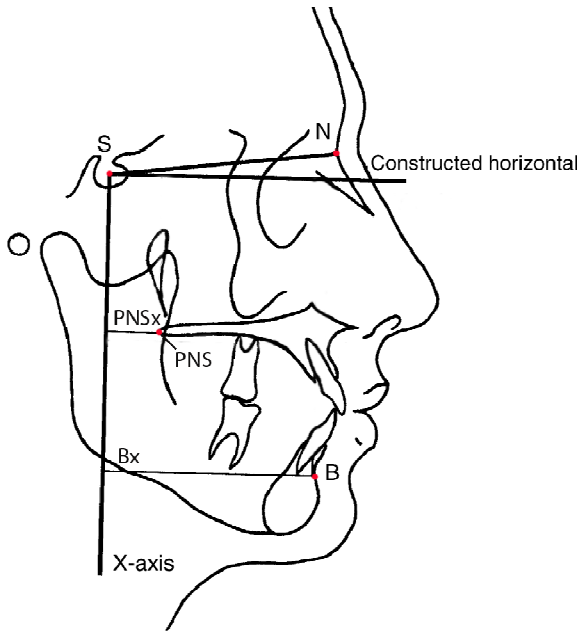


Figure 3. Skeletal measurements.

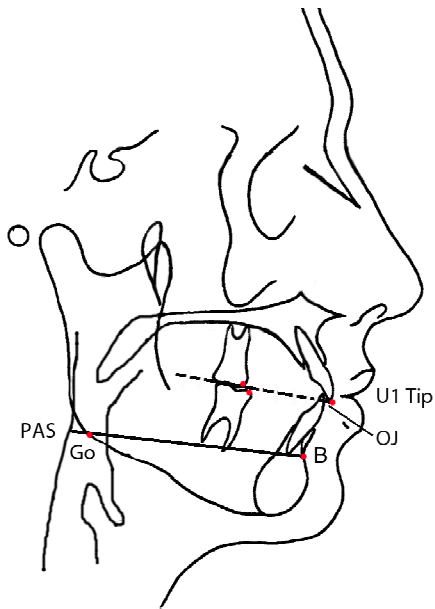


Figure 4. Dental and soft tissue airway measurements

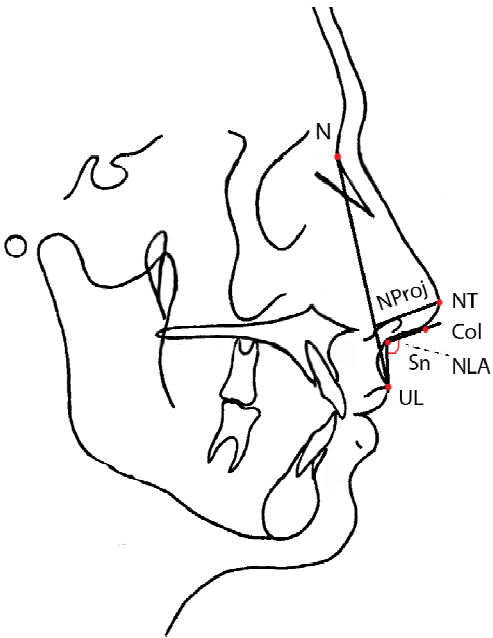


Figure 5. Soft tissue nasal measurements

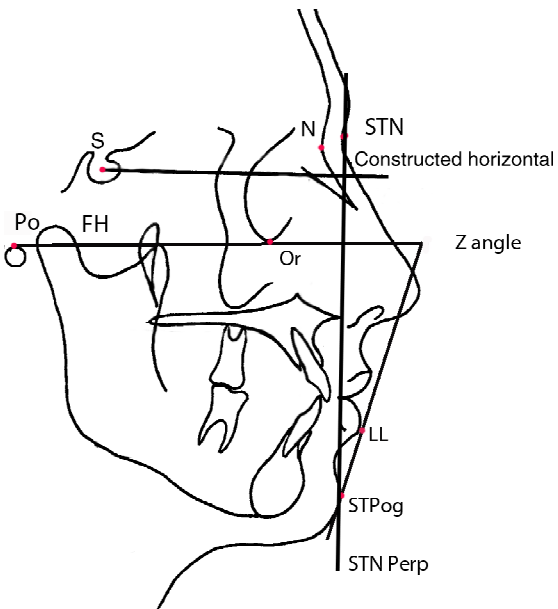


Figure 6. Soft tissue chin measurements

Figure 7 : Epworth Sleepiness Scale & Long-term Questionnaire

Questionnaire

1. What is your current height and weight? _____
2. Did you have improvement in your OSA after the surgery and orthodontic treatment? **Yes** **No**
3. If no, please explain

4. Did you seek any further surgery for your OSA after the previous surgical treatment? **Yes** **No**
5. If no, please explain

6. Are you currently using a CPAP or other device to improve your OSA?
Yes **No**
7. If other, please explain

8. Are you pleased with your facial appearance after the surgery?
Yes **Neutral** **No**
9. Would you recommend the surgical treatment to others?
Yes **No**

Epworth Sleepiness Scale

Use the following scale to choose the most appropriate number for each situation:

- 0 = would *never* doze or sleep.
- 1 = *slight* chance of dozing or sleeping
- 2 = *moderate* chance of dozing or sleeping
- 3 = *high* chance of dozing or sleeping

Situation

Chance of Dozing or Sleeping

Sitting and reading	
Watching TV	_____
Sitting inactive in a public place	_____
Being a passenger in a motor vehicle for an hour or more	_____
Lying down in the afternoon	_____
Sitting and talking to someone	_____
Sitting quietly after lunch (no alcohol)	

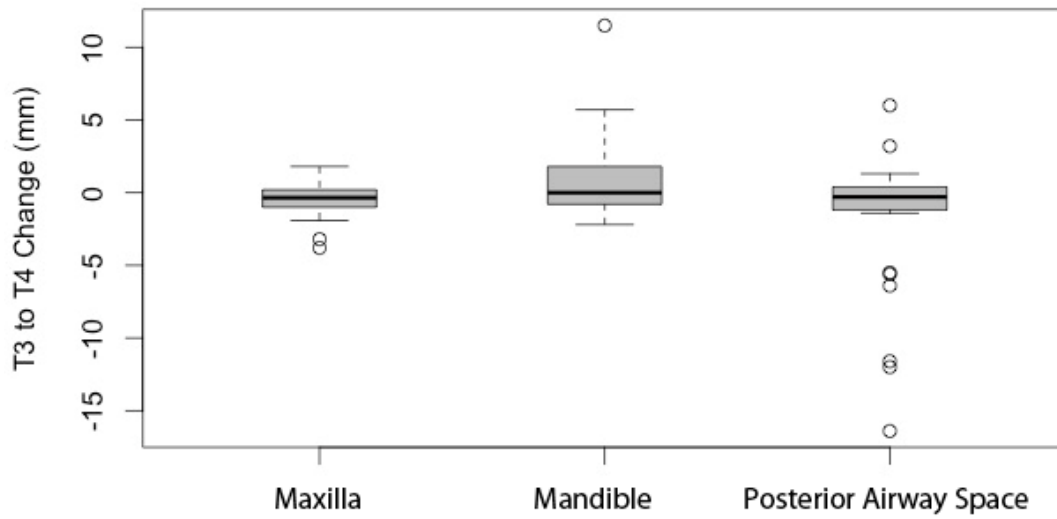


Figure 8. Soft tissue and skeletal changes from post-surgical (T3) to final timepoints(T4). Ceph sub-sample (N=29)

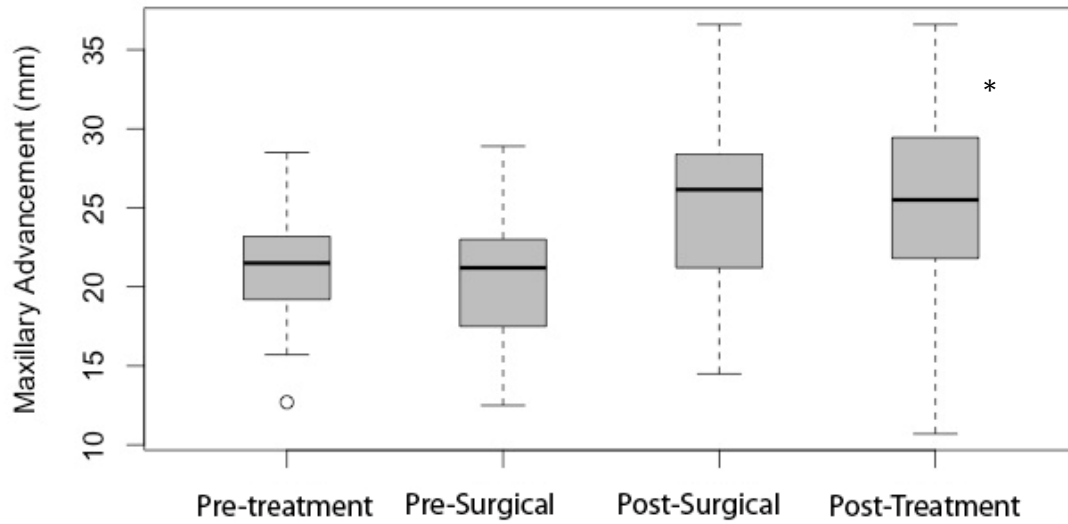


Figure 9. Maxillary skeletal changes throughout treatment measured as the difference in distance pns from vertical x-axis. Ceph sub-sample (N=29) * P < 0.05

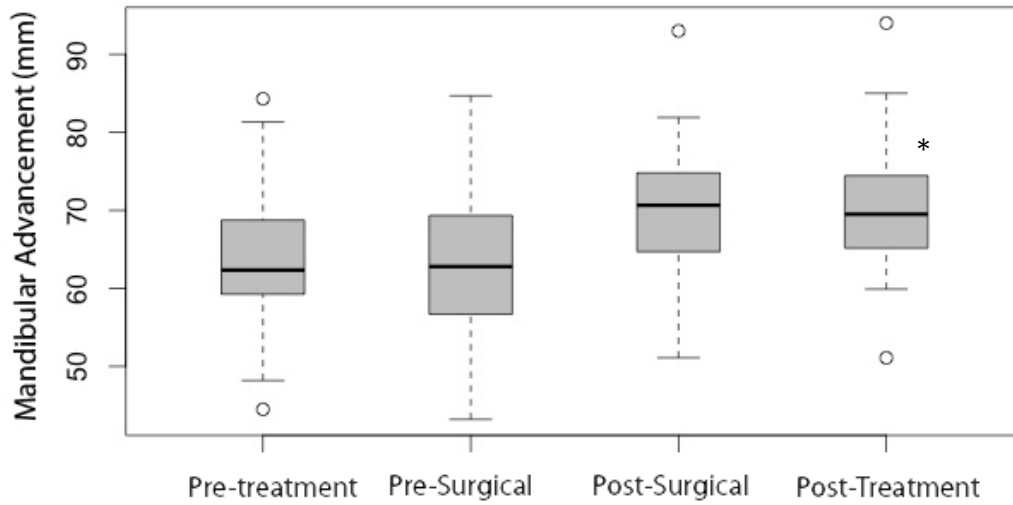


Figure 10. Mandibular skeletal changes throughout treatment measured as the difference in distance pns from vertical x-axis. Ceph sub-sample (N=29) * P <0.05

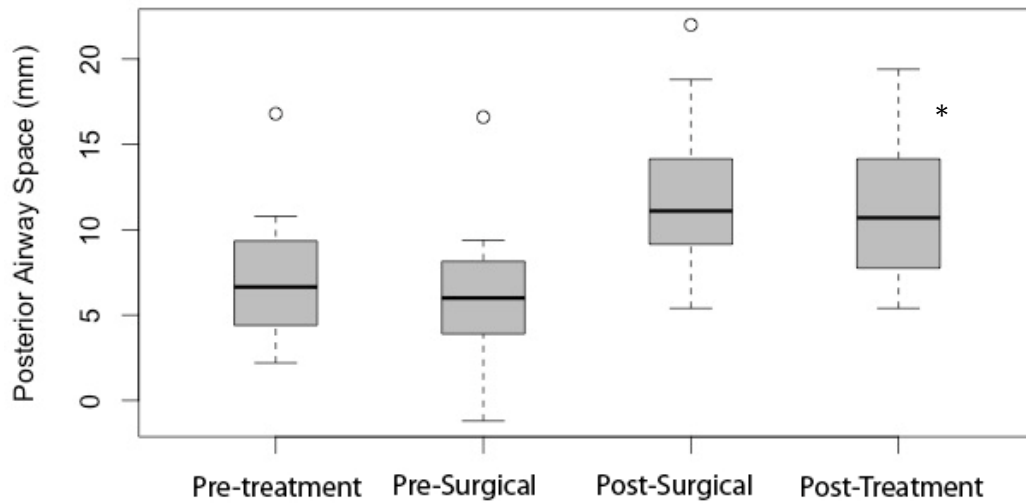


Figure 11. Posterior airway space changes throughout treatment. Ceph sub-sample (N=29)
* P <0.05

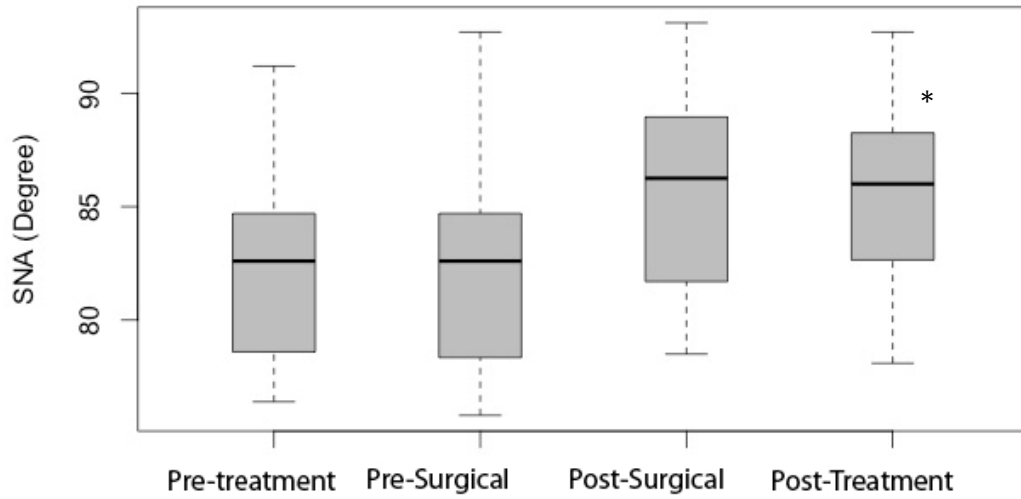


Figure 12. SNA angular changes throughout treatment. Ceph sub-sample (N=29)
 * P < 0.05

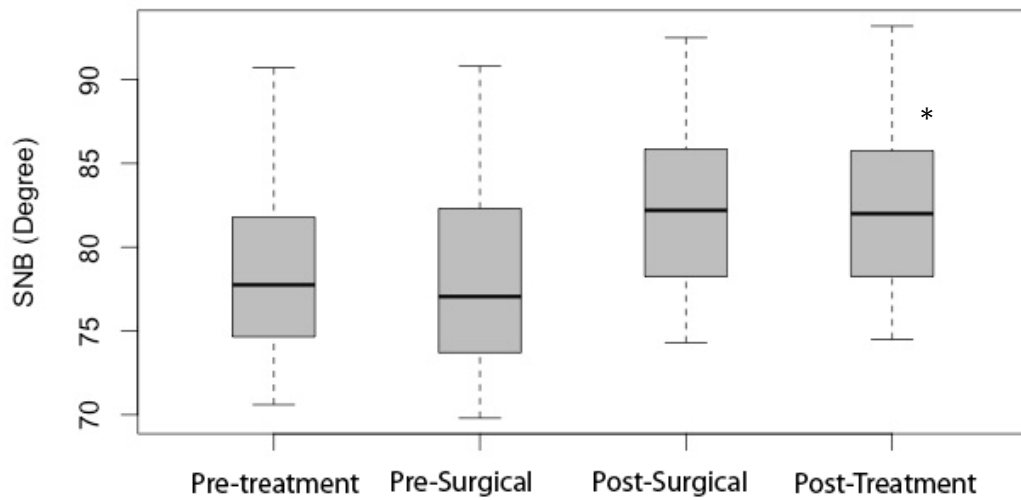


Figure 13. SNB angular changes throughout treatment. Ceph sub-sample (N=29)
 * P < 0.05

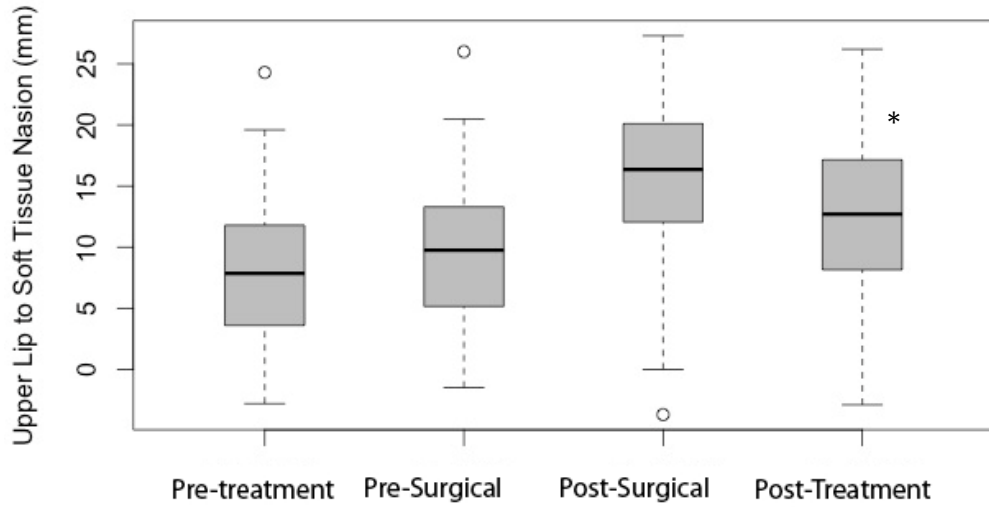


Figure 14. Upper lip changes throughout treatment from soft tissue nasion. Ceph sub-sample (N=29) * P <0.05

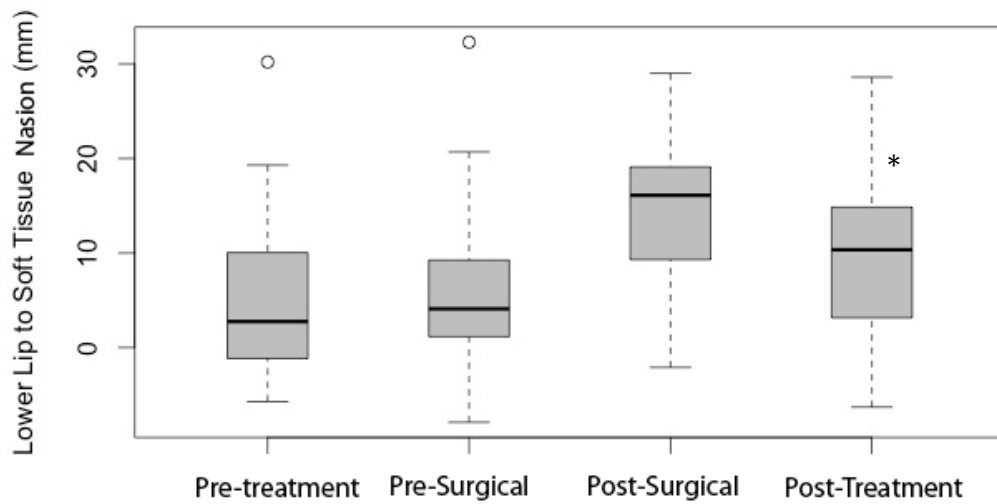


Figure 15. Lower lip changes throughout treatment from soft tissue nasion. Ceph sub-sample (N=29) * P <0.05

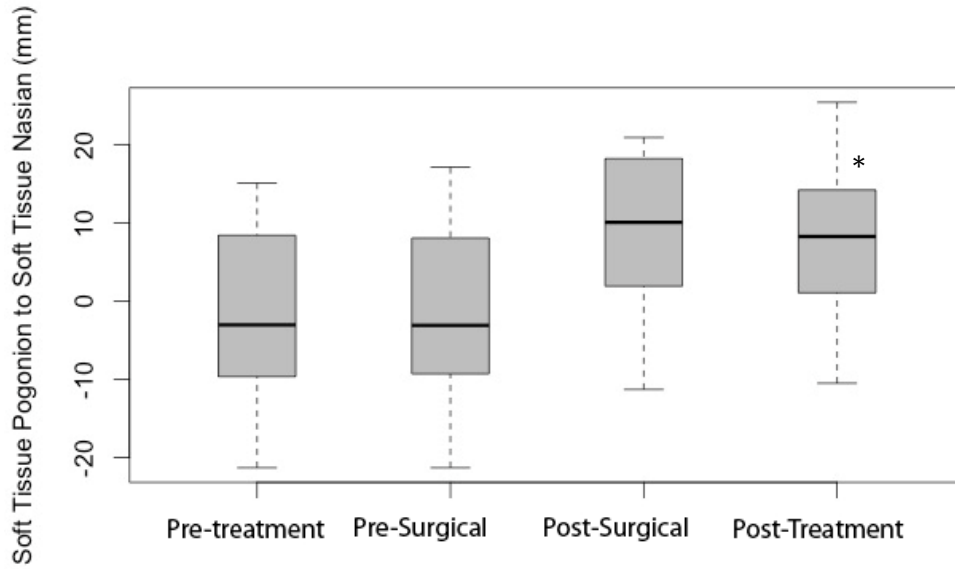


Figure 16. Soft tissue chin changes throughout treatment. Ceph sub-sample (N=29)
 * P < 0.05

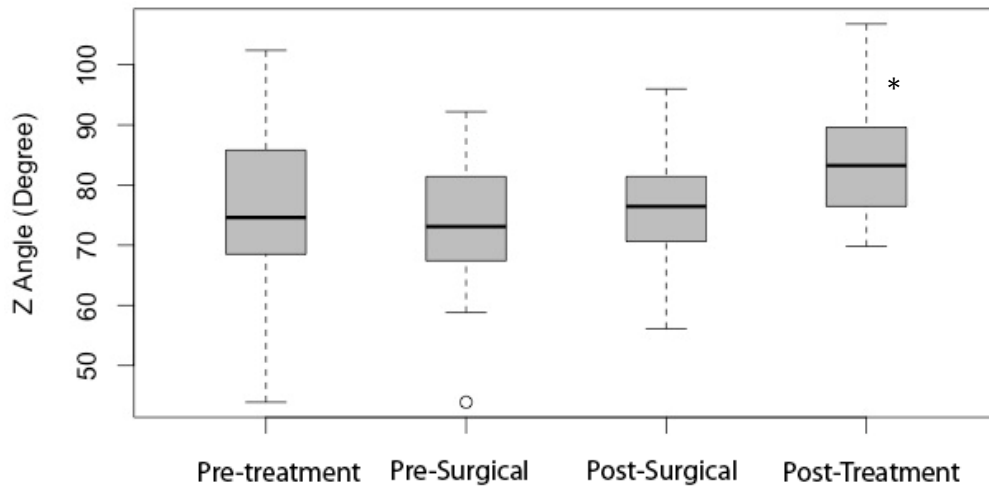


Figure 17. Z-angle changes throughout treatment. Ceph sub-sample (N=29)
 * P < 0.05

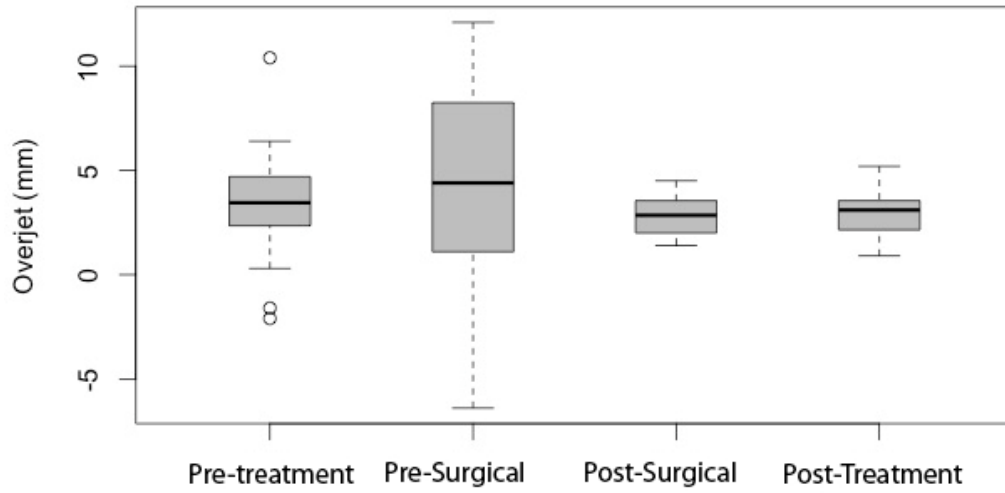


Figure 18. Dental changes throughout treatment. Ceph sub-sample (N=29)

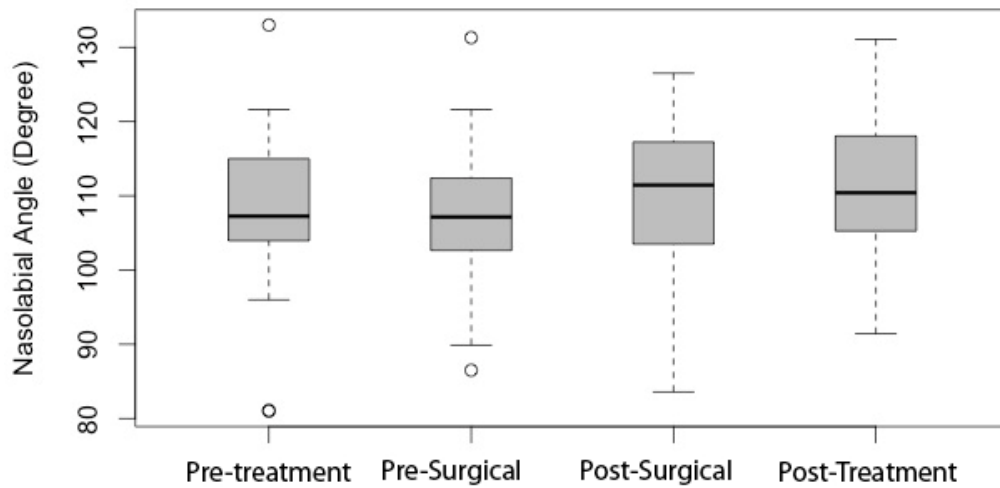


Figure 19. Nasal angular changes throughout treatment. Ceph sub-sample (N=29)

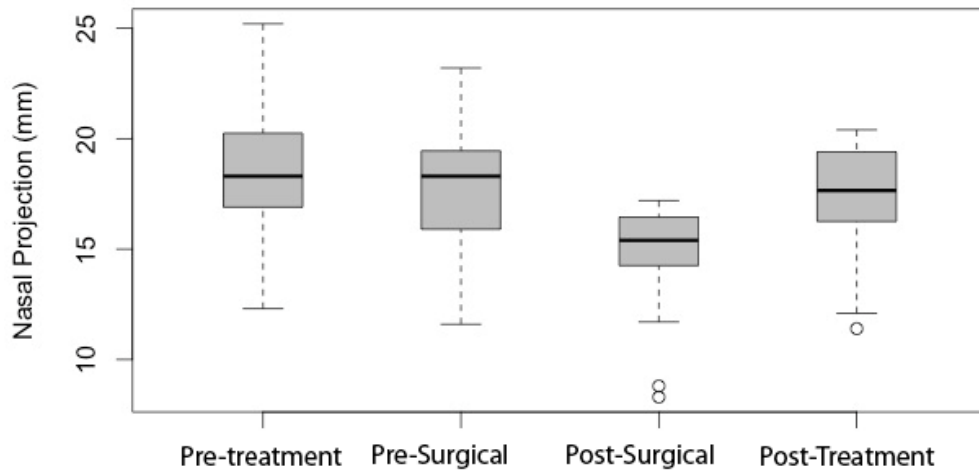


Figure 20. Soft tissue nasal projection changes throughout treatment. Ceph sub-sample (N=29)

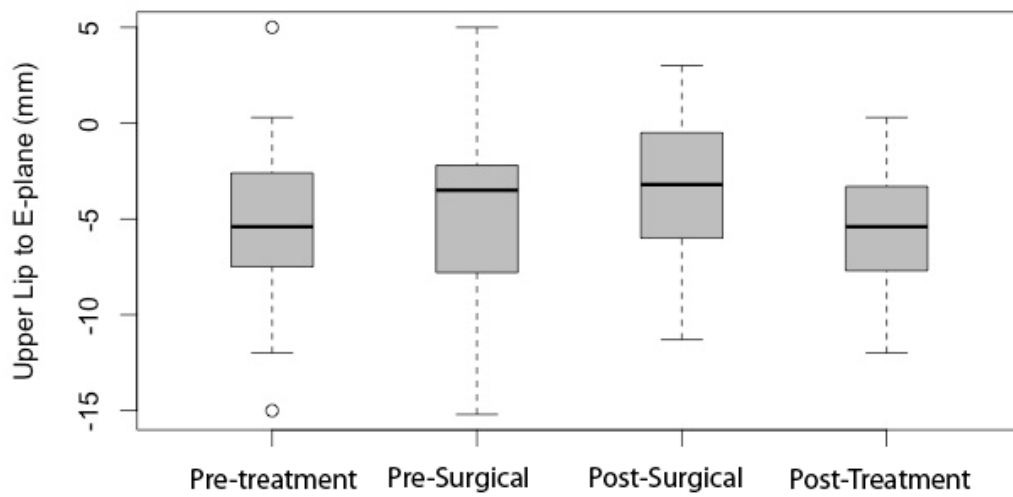


Figure 21. Upper lip changes throughout treatment from E-line. Ceph sub-sample (N=29)

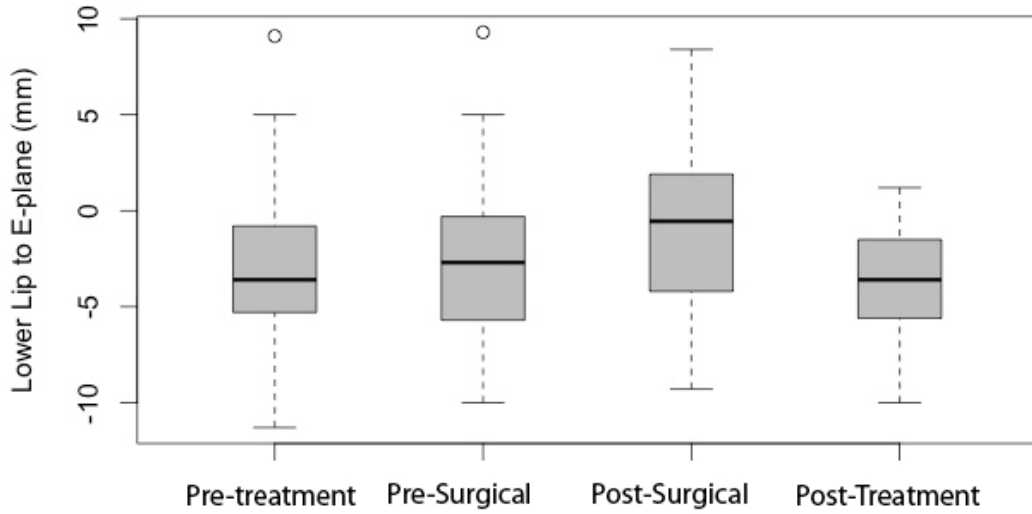


Figure 22. Lower lip changes throughout treatment from E-line. Ceph sub-sample (N=29)

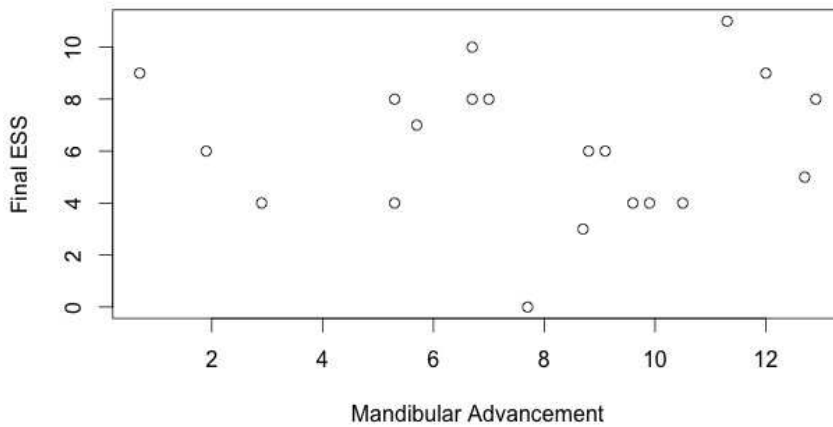


Figure 23. Scatterplot of Epworth Sleepiness Scale (ESS) and Mandibular Advancement. ESS sub-sample (N=22)

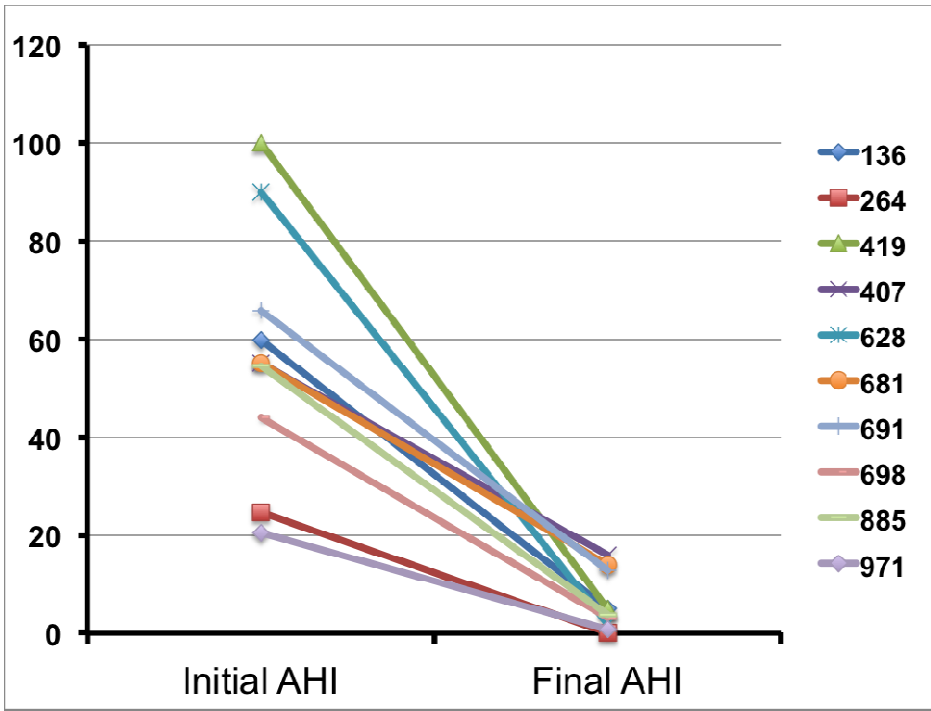


Fig. 24. The initial AHI (Apnea-Hypopnea Index; events/hr) and final AHI (6 months after MMA). AHI sub-sample (N=12)

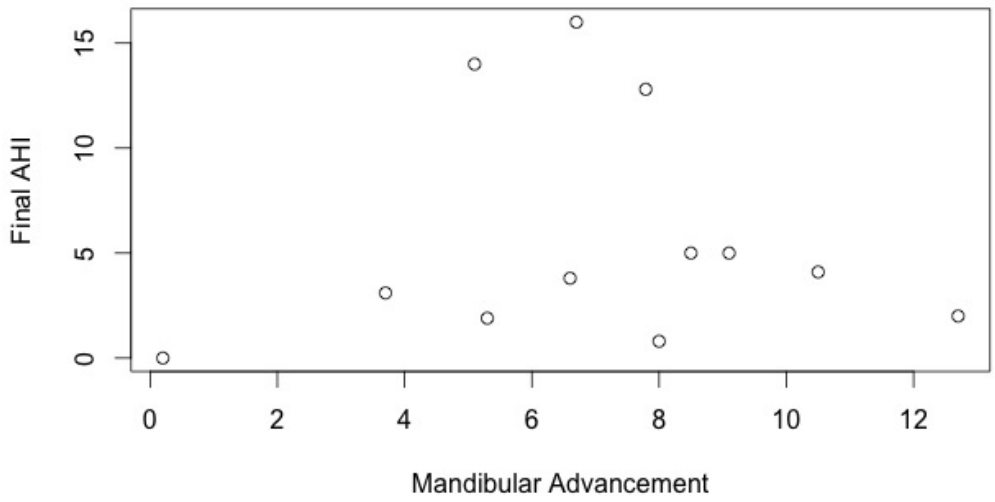


Figure 25. Scatterplot of final Apnea-Hypopnea Index and Mandibular Advancement. AHI sub-sample (N=12)