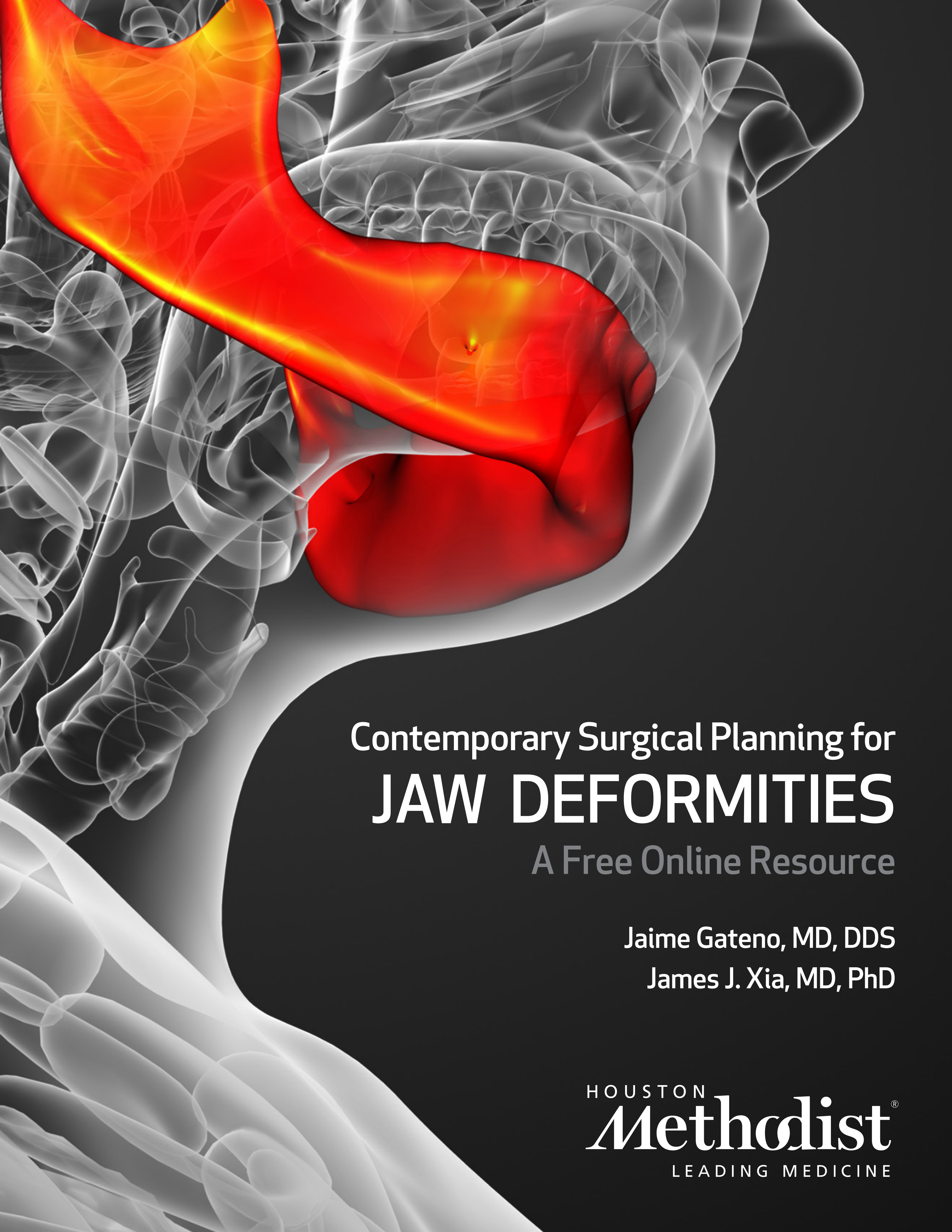

Contemporary Surgical Planning for

JAW DEFORMITIES

A Free Online Resource

Jaime Gateno, MD, DDS

James J. Xia, MD, PhD

HOUSTON Methodist® LEADING MEDICINE

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Acknowledgments

I confess that when one is fully engaged in clinical practice and research, finding a sense of perspective can be challenging—and never more so than with oral and maxillofacial surgery, which for 50 years emphasized materials and techniques that enabled only incremental progress. Thankfully, for the past two decades, we have been advancing toward the sophisticated surgical planning required to truly optimize patient outcomes. Please know that I am singularly grateful to have embarked upon my career during the latter era. For more than 17 years, my brilliant team and collaborators across the world have focused on developing and refining surgical planning methodologies to progressively achieve more precise results.

First and foremost, I want to express my deepest appreciation to the wonderful, courageous patients who have trusted me; my research partners and colleagues, as we have devised, honed, and disseminated our meticulous planning processes for oral and maxillofacial surgery.

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It is with great warmth and enthusiasm that I acknowledge my close colleague and role model, Leonard B. Kaban, DMD, MD, FACS. Dr. Kaban, or Lenny—as he is known to his associates and friends—is the former chief of oral and maxillofacial surgery at Massachusetts General Hospital and the previous chairman of oral and maxillofacial surgery at Harvard School of Dental Medicine (HSDM). Lenny is internationally renowned for his work in the treatment of children with craniofacial abnormalities, jaw deformities, jaw tumors, TMJ deformities, salivary gland disease, secondary cleft lip/palate deformities, obstructive sleep apnea, micrognathia and facial trauma. His landmark translational research includes the development of distraction osteogenesis for mandibular advancement, bone wound healing, and tissue engineering. Lenny is an abiding inspirational force in my life, and I know many others would report the same.

Of course, private philanthropy, extramural funding, and seminal advice have played a significant role in facilitating the development of our program at Houston Methodist. I am tremendously grateful to the Albert and Margaret Alkek Foundation for generously agreeing to support the publication of this book; more specifically, I would thank Margaret Alkek Williams, chairman; Charles A. Williams, president; Randa Duncan Williams, vice president; Scott B. Seaman, executive director; and Sandra K. Bacak, controller. On the research side, Dr. James Xia and I would like to acknowledge the following extramural funding sources: NIH/NIDCR R41/R42 DE016171, NIH/NIDCR R01 DE022676, NIH/NIDCR R01 DE021863, and NIH/NIDCR R01 DE022676 (renewal). Last, but not least, I want to extend special thanks to my esteemed friend, Rahul Metha, for his invaluable advice.

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Finally, allowing that no human enterprise can be successful without the knowledge and support afforded us by those who came before—as well as those who have believed in us along the way—

the reality is that many heroes will remain unsung in this acknowledgment. I nonetheless recognize an immense debt of gratitude for your contributions—past, present, and future.

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WHAT ARE JAW DEFORMITIES?

Deformity is defined as abnormal form; disfigurement; loss of the natural arrangement.[1] Humans have two jaws—an upper and a lower—and jaw deformities are disfigurements of one or both jaws. The lower jaw is a single bone, the mandible (Figure 1). The upper jaw is a functional unit composed of four separate bones: the right and left maxillae and the right and left palatine bones; with regard to the latter, we are more specifically referencing the parts of these bones located below the zygoma (*i.e.*, the cheek or malar bone). Clinically, the upper jaw is also called the 'maxilla,' a term that can be confusing because it is also the name of a bone (Figure 1). Henceforth, the term maxilla will be used to refer to the upper jaw.

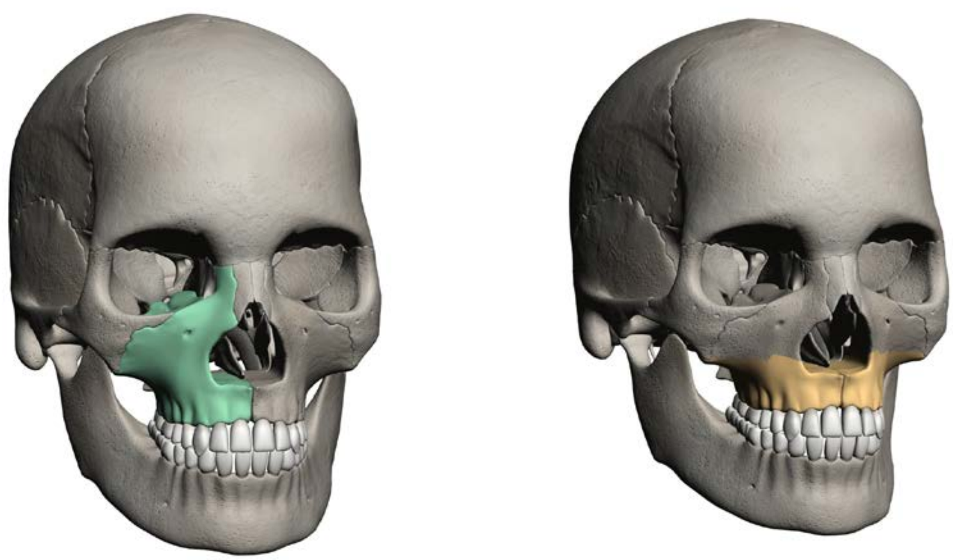


Figure 1. Left figure: maxillary bone (green). Right figure: maxilla, or upper jaw (brown).

Some jaw deformities occur *in utero* and are present at birth, while others are acquired later in life. They originate from many causes: genetic abnormalities, deformations, intrauterine disruptions, diseases, injuries, or abnormal function.

Jaw deformities affect at least one of the geometric properties of the jaws:

- Size
- Position
- Orientation
- Shape
- Symmetry

For a given patient, a jaw deformity can be the primary problem or it can be secondary to disease, injury, or functional impairment. One instance of a patient for whom a deformity is the primary problem is a woman with a familial history of mandibular prognathism who has developed this condition during puberty. Examples of secondary deformities include a young man with an anterior open-bite from condylar destruction resulting from juvenile arthritis (a disease), a teenager with retrognathia and facial asymmetry caused by condylar fracture and TMJ ankylosis during childhood (an injury), and a patient with anterior open-bite due to mouth-breathing (functional impairment).

Classification of Jaw Deformities

In the United States, the most widely used classification system for jaw deformities is that provided by the Center for Medicare and Medicaid Services and the National Center for Health Statistics. This classification is part of the International Classification of Diseases, Clinical Modification (ICD-CM), a taxonomy scheme based on the World Health Organization's International Classification of Diseases (ICD), which is the traditional standard diagnostic tool for epidemiology, health management, and clinical care.[2]

The latest iteration of the ICD-CM, version 10,[3] sorts jaw deformities geometrically into only 3 groups: anomalies of jaw size, anomalies of jaw-cranial base relationship, or unspecified (Table 1).[4]

Table 1. Jaw deformity nomenclature.

Category	Aspect	Names
Size	Too big	Hyperplasia, macrognathia, macrogenia
	Too small	Hypoplasia, micrognathia, microgenia
Position	Anteroposterior	Prognathism, retrognathism
	Transverse	Laterognathia
	Vertical	Excessive downward displacement, insufficient downward displacement
Orientation		Malrotation
Shape		Distortion
Completeness		Agenesis, cleft, defect
Symmetry	Object	Asymmetry
	Alignment	Asymmetric alignment

However, these deformities can affect 6 different geometric attributes: size, position, orientation, shape, symmetry, and completeness.

In both clinical practice and teaching, we have found the ICD-CM classification system incomplete and disjointed. Because of these deficiencies, we have developed what we consider to be a better alternative. It is introduced in the following section.

Geometric Classification of Jaw Deformities

Our classification scheme is presented as a mind-map in Figure 2.[4] The scheme first classifies jaw deformities as either osseous or dental. Osseous deformities affect the jawbones; dental deformities affect the teeth.

The classification recognizes the jawbones as having 6 geometric attributes: size, position, orientation, shape, symmetry, and completeness. Jaw deformities are classified according to the attribute they affect.

Deformities of *size* occur when a jaw is either too large or too small. The term *hyperplasia* indicates pathological enlargement, whereas *hypoplasia* signifies the failure to attain normal size. *Micrognathia* is a synonym for *mandibular hypoplasia*, while *macrognathia* corresponds to *mandibular hyperplasia*. The terms *macrogenia* and *microgenia* also refer to size, with macrogenia indicating a large and microgenia a small chin.

Abnormal jaw *positions* occur in all cardinal directions. *Prognathism* and *retrognathism* are deformities characterized by abnormal anteroposterior position. By convention, anteroposterior position is assessed in relation to the cranial base. Prognathism occurs when a jaw is too far forward, and retrognathism when it is too far backward. In the transverse direction a jaw can be displaced, in either direction, away from the median plane, a deformity called *laterognathia*. Vertically, a jaw can be too far down—*excessive downward displacement*—or too far up—*deficient downward displacement*.

When a jaw is *abnormally oriented,* malrotations occur. These *malrotations* are classified according to the axis on which the abnormal rotation occurs. When a jaw is malrotated around the transverse facial axis, it is said to have *abnormal pitch*. When malrotated around the anteroposterior axis, the jaw has an *abnormal roll*, a condition also known as *cant*. Finally, when a jaw is malrotated around the vertical axis, it has *abnormal yaw*.

Shape refers to figure, the geometric characteristic of an object that is not size, position, or orientation.[5] A jaw with abnormal shape is said be *distorted*.

The human face has *reflection symmetry* around one plane, the *median*. For facial symmetry to exist, two conditions must be met.[6] First, each of the units comprising the face must be symmetrical, a condition called *object symmetry*. Second, each of the units must be symmetrically aligned to the median plane, a condition called *symmetric alignment*. Jaws can have deformities of symmetry, either because of object asymmetry or because of misalignment. The terms *mandibular asymmetry* and *maxillary asymmetry* refer to abnormalities in object symmetry; whereas, the term *asymmetric alignment* is used to denote abnormal alignment causing asymmetry.

Completeness refers the wholeness of the jaw. A jaw can be incomplete because one of its processes did not fully develop; for example, *agenesis* of the condylar process of the mandible, which may be seen in hemifacial microsomia. Completeness can also fail to occur because some of the jaw's embryologic processes failed to fuse (*e.g.*, cleft), or because of an acquired defect.

The different types of jaw deformities (size, position, orientation, shape, symmetry, and completeness) are frequently correlated.[6, 7] For example, *asymmetric alignment* cannot occur in the absence of at least one other deformity (*i.e.*, laterognathia, abnormal roll, or abnormal yaw).

As stated above, jaw deformities can also affect the teeth. Like the ICD-CM[3], our classification scheme only considers dental deformities that engender malocclusion. Malocclusion can result from the disarrangement of one or more teeth in their dental arch or because the upper and lower dental arches are not coordinated (Figure 2).

Within a dental arch, deformity may affect the alignment, leveling, or spacing of teeth. *Alignment* refers to the arrangement of teeth in an arch. In ideal alignment, the incisal edges of the incisors and the buccal-cuspal ridges of the canines, premolars, and molars form an arch. Misalignment can occur because of dental displacement, dental tipping, or dental rotations. In *displacement*, a tooth is bodily moved outside the arch. In *tipping*, a tooth is abnormally inclined. In *rotations*, a tooth is misaligned because of abnormal rotation around its long axis.

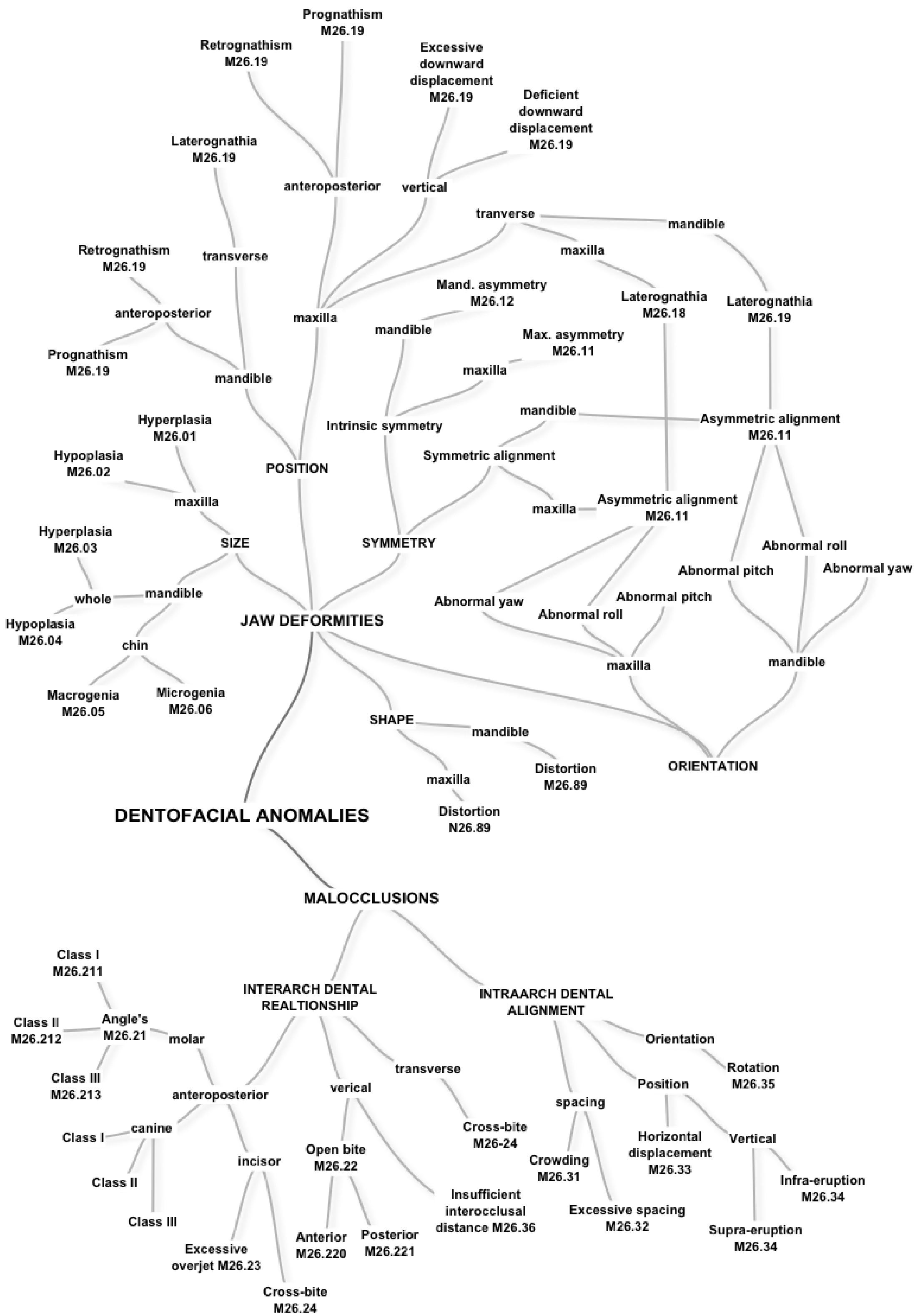


Figure 2. Mind-map of the different dentofacial deformities.

Leveling refers to the vertical arrangement of teeth. Abnormal leveling can affect a single tooth or the whole arch. For this assessment, one measures the vertical position of the teeth in relation to their occlusal plane. In other words, one measures the vertical positions of the lower teeth in relation to the mandibular occlusal plane and the vertical positions of the upper teeth in relation to the maxillary occlusal plane.

An individual tooth is in *infraocclusion* or *supraocclusion* when it is located below or above its ascribed occlusal plane. For the entire dental arch, one judges dental leveling by gauging the *curve of Spee*. From the central incisor backward to the last molar, the cusps of all teeth should inscribe either a flat plane or a curved plane of slightly upward concavity. Dental deformity can create a *deep* or a *reverse* curve of Spee. A curve of Spee is *deep* when the cusps of the teeth trace a plane with sharp upward curvature. The curve is *reversed* when the curvature of the plane has downward concavity.

Within a dental arch, the teeth should be normally spaced; that is, adjacent teeth should touch without crowding one another. Spacing is abnormal when diastemas are present or when the arch cannot accommodate the teeth. The first condition is *excessive dental spacing*; the second is *dental crowding*.

In addition, dental deformities can occur when the upper and lower arches are not harmonized. For normal occlusion to occur, it is insufficient for the upper and lower teeth to be normally arranged in an arch. The upper and lower dental arches must also be coordinated: in position, shape, and tooth size.

Discordant dental arch positions cause malocclusion. This lack of concordance can occur among all cardinal planes: anteroposterior, vertical, and transverse.

We appraise anteroposterior occlusal relationships at three different sites. They are: first molar, canine, and central incisors. In this appraisal, the frame of reference is the upper dentition; that is, the examiner judges the anteroposterior position of the lower teeth in relation to hypothetical static upper teeth.

Angle's molar relationship assesses the position of the buccal groove of the lower first molar in relation to the mesiobuccal cusp of the upper.[8] In an ideal Class I molar relationship, these landmarks coincide. In a Class II relationship, the lower molar groove is behind the upper cusp; with a Class III, it is in front. A similar assessment is done in the canine region. In a Class I canine relationship, the lower-canine-first-premolar embrasure coincides with the cusp of the upper canine. In a Class II, the embrasure is behind the upper canine cusp; with a Class III, it is in front. Finally, in the incisal region, we measure the overjet. *Overjet* is the horizontal distance between the incisal edges of the upper and lower central incisors. When the lower incisal edge coincides with the upper, the overjet is zero. When it is behind, the measurement has a positive value; in front, it is negative. The ideal overjet is +2 mm.

Based on these assessments, one classifies the occlusion into *neutrocclusion*, *distocclusion*, or *mesiocclusion*. In neutrocclusion, the molar and canine relationships are Class I and the overjet is normal. In distocclusion, the molar and canine relationships are Class II and the overjet is either greater than normal (Division 1) or normal (Division 2). In mesiocclusion, the molar and canine relationships are Class III and the overjet is smaller than normal, usually negative.

Position discordance between the upper and lower dental arches also occurs in the vertical direction. Absence of vertical overlap between the upper and lower teeth produces an *open bite*. It can be can *anterior* or *posterior*.

Excessive vertical-overlap of the anterior teeth results in *deep bite*. Excessive vertical-overlap of the posterior teeth results in *posterior bite collapse*. The latter condition can only occur when many posterior teeth are missing and the remaining teeth have no opposing occlusion or when there is complete crossbite of the posterior teeth.

Finally, discordance between the maxillary and mandibular dental arches can also occur in the transverse dimension. Normally, the buccal cusps of the maxillary posterior teeth are lateral to the buccal cusps of the mandibular teeth. When the reverse occurs, we encounter a *posterior crossbite*. In extreme cases, all the lower teeth can be inside the upper, a condition known as *Brodie bite*. Conversely, the upper teeth can be inside the lower, a condition known as *scissor bite*.

As previously mentioned, the upper and lower arches can occlude abnormally because they have different shapes. For example, a "U" shaped lower arch does not fit a "V" shaped upper. The lack of shape congruency between the upper and lower teeth results in *arch shape-discordance*.

Ultimately, to obtain good dental interdigitation in Class I occlusion, the width (mesio-distal size) of the lower teeth must be proportional to the width of the upper.[9] When this proportionality is absent, the dental arches have a *tooth size discrepancy*.

Indications for Treatment

A jaw deformity can be corrected with surgery. Yet, the mere presence of a deformity is not enough to warrant surgery. Surgery is indicated when the deformity is sufficiently severe that it cannot be camouflaged through a simpler treatment (*e.g.*, orthodontics, genioplasty, etc.). Moreover, it must cause impairment or comorbidity. The impairment can be one of appearance or one of function (*e.g.*, mastication, speech, breathing, or socialization, etc.). Comorbidities, which are concurrent conditions related to the primary condition, may also be present. Examples of comorbidities associated with jaw deformities are obstructive apnea, TMJ derangement, and occlusal soft-tissue impingement.

Evaluation of Patients with Jaw Deformities

Evaluation is a structured process that begins with the patient encounter and ends in an assessment. It has three steps: history, physical examination, and the appraisal of diagnostic studies. In the case of a patient with a jaw deformity, the end result of the evaluation (the assessment) should include:

- A primary diagnosis
- Secondary diagnoses and comorbidities, if present
- A statement detailing the severity of the deformity
- A list of impairments caused by the deformity

During the evaluation, the provider should collect all data necessary to undertake and complete the assessment process.

History

The history is obtained by interviewing the patient and is, therefore, the subjective component of the evaluation. It has multiple parts, including:

- Chief complaint(s)
- History of the present illness
- Past medical history
- Review of systems

The chief complaint describes the patient's *symptoms* or *problems*. It should not be a statement of treatment (*e.g.*, "I need surgery"). Examples of suitable chief complaints are: "I have difficulty chewing," "my bite is off," and/or "my face is crooked."

The history of the present illness should comprehend the following:

- When did the deformity first become apparent and how did it evolve?
- Does the patient have chewing problems? In trying to ascertain this, one should be specific when questioning patients. Many tend to answer "no" to the general question: *Do you have chewing problems?* Yet they may answer in the positive when asked a more explicit question like: *Can you cut food with your front teeth* (*i.e.*, incising)?
- Does the patient have breathing problems (*e.g*., mouth-breathing, snoring, or witnessed apnea)?
- Does the patient have speech problems?
- Does the patient have social or emotional problems related to the deformity?
- Does the patient have other comorbid conditions? One should ask about TMJ symptoms (*e.g.*, joint pain, joint noises, limited or abnormal motion), soft-tissue impingements, and/or other diseases that may affect the jaws.

Physical Examination

In this section, the authors present a *problem-focused* physical examination aimed at evaluating jaw deformities. The examination is divided into two parts: an assessment of facial form and a cursory evaluation. The purpose of the first is to determine the presence, extent, and severity of a deformity; the second seeks to identify signs of disease. The assessment of facial form includes evaluations of facial soft-tissue and dentition. The goal is to diagnose a jaw deformity; however, as the skeleton cannot be inspected, one infers bone deformity by appraising facial appearance and dentition.

During the physical examination, the examiner must determine the size, position, orientation, shape, and symmetry of the jaws. Assessing three of these properties—position, orientation, and symmetry—requires a frame of reference, the most useful of which is that defined by the *standard anatomical planes*: median, coronal, and axial.[6, 7, 10] The *median plane* (*i.e.*, the plane of symmetry of the face) divides the face into right and left halves; the *coronal plane* divides the face into anterior and posterior portions; and the *axial plane* divides the face into upper and lower segments. These planes are mutually perpendicular, or orthogonal. The lines of intersection between the planes form the axes of the face. The intersection of the medial and axial planes forms the *anteroposterior axis*, the intersection of the medial and coronal planes forms the *vertical axis*, and the intersection of the axial and coronal planes forms the *transverse axis*. These axes define the cardinal directions of the face: front, back, cranial, caudal, right, and left (Figure 3).

Throughout the physical examination, the planes of our reference system (*i.e.*, median, axial, and coronal) are imaginary. We mentally construct them, while observing the patient in a *standard reference posture*.

The standard reference posture of the head is the *natural head posture* (NHP).[10-12] The NHP is a component of *standard international anatomical alignment*, a reference position in which a subject is standing erect, feet together, and hands to the side, with the face looking forward toward the horizon. In this posture the head is not flexed or extended, nor is it rotated or tilted.

Clinical Assessment of Jaw Position

During the physical examination, one determines the position of the maxilla and mandible in three-dimensional space. This is done separately for each facial axis: anteroposterior, vertical, and transverse.

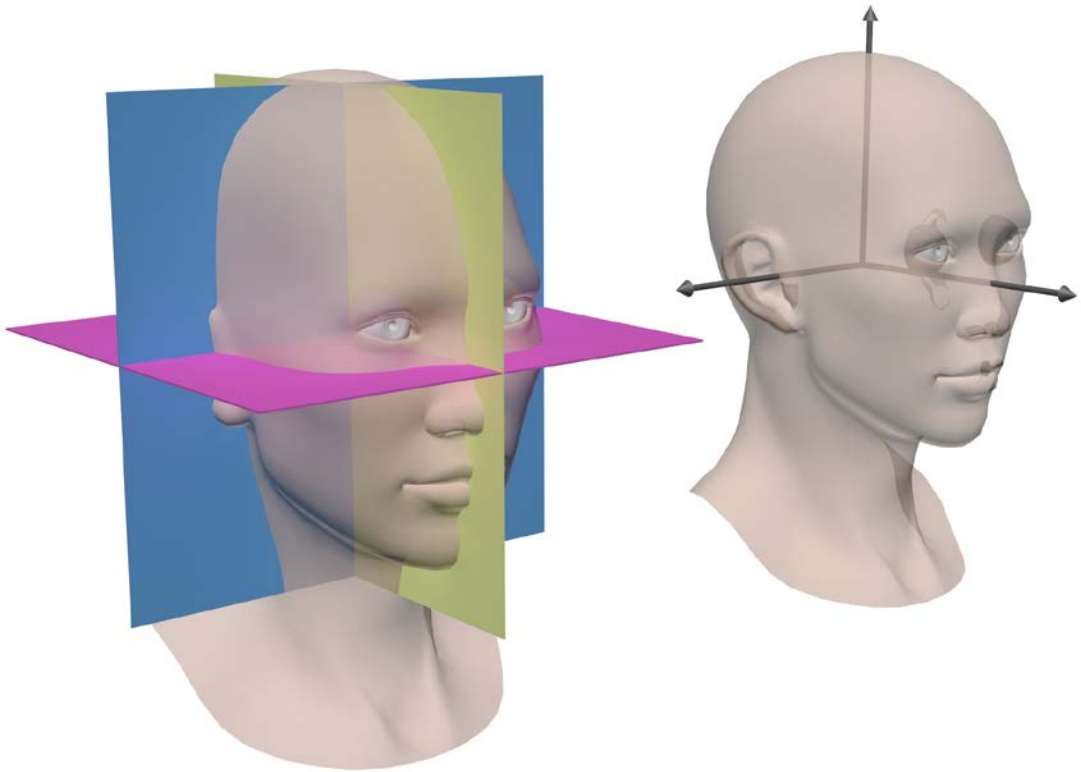


Figure 3. Standard anatomical frame of reference. Left figure shows planes. Right figure shows axes.

ANTEROPOSTERIOR

One infers the anteroposterior position of the jaws by evaluating the anteroposterior occlusal relationships and the facial profile. The occlusal relationships are appraised at three different sites: first molar, canine, and central incisor (Figure 4). With this appraisal, the frame of reference is the upper dentition and the examiner gauges the anteroposterior position of the lower teeth in relation to a hypothetical static upper.

Angle's classifications of molar relationship assesses the position of the buccal groove of the lower first molar in relation to the mesiobuccal cusp of the upper.[13] In an ideal Class I molar relationship, these landmarks coincide (*i.e.*, align). In a Class II relationship, the lower molar groove is behind the upper cusp; whereas, in a Class III, it is in front. The canine region is assessed in a similar manner. In a Class I canine relationship, the lower-canine-first-premolar embrasure coincides with the cusp of the upper canine. In a Class II, the embrasure is behind the upper canine cusp; with a Class III, it is in front.

Finally, for the incisal region, we measure the overjet, which is defined as the horizontal distance between the incisal edges of the upper and lower central incisors. When the lower incisal edge coincides with the upper, the overjet is zero. When it is behind, the measurement has a positive value; when in front, it will be negative. The ideal overjet is +2mm.

Based on the above referenced assessments, one classifies the occlusion into neutrocclusion, distocclusion, or mesiocclusion. In neutrocclusion, the molar and canine relationships are Class I and the overjet is normal. In distocclusion, the molar and canine relationships are Class II and the overjet is either greater than normal (Division 1) or normal (Division 2). In mesiocclusion, the molar and canine relationships are Class III and the overjet is smaller than normal, usually negative.

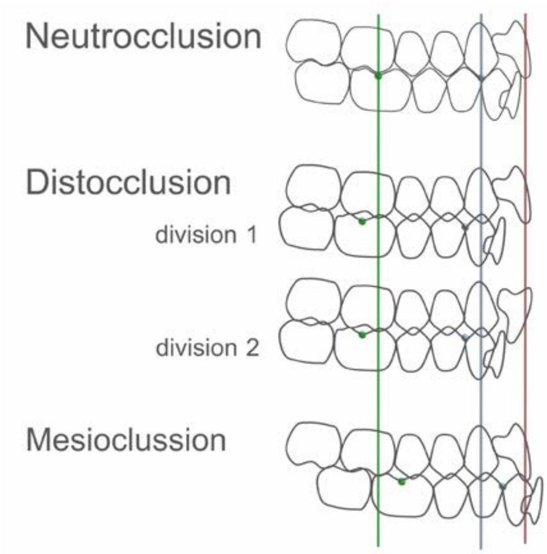


Figure 4. Assessment of anteroposterior Position (occlusion).

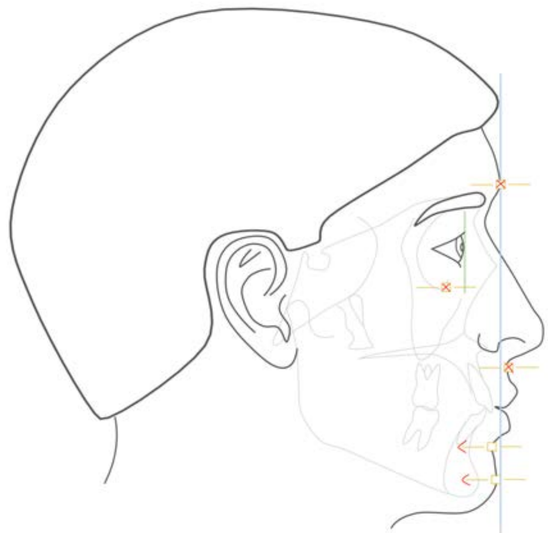


Figure 5. Assessment of anteroposterior position (profile).

Distocclusion can occur in many different configurations:

- Backward-positioned mandible with a normally positioned maxilla
- Backward mandible with a forward maxilla
- Backward mandible with a less backward maxilla
- Normal mandible with forward maxilla
- Forward mandible with more forward maxilla

Thus, the finding of mesiocclusion or distocclusion reveals a discrepancy in jaw position between the upper and lower jaws, and cannot be used independently to determine anteroposterior jaw position. Also note that the finding of neutrocclusion does not necessarily imply normal anteroposterior jaw position, as both jaws can be retrognathic or prognathic.

To complete the assessment of anteroposterior jaw position, one also evaluates the facial profile.[13-16] Traditionally, clinicians have assessed the profile by classifying it into one of three categories: straight, convex, or concave. However, this assessment lacks specificity. For example, a concave profile can occur when the upper jaw is normal and the lower jaw is prognathic, when the upper jaw is retrognathic and the lower jaw is normal, or when the upper jaw is retrognathic and the lower jaw is prognathic.

A better method is to compare the anteroposterior position of each jaw with the anterior boundary of the cranial base. Three structures related to the anterior cranial base—soft-tissue glabella, soft-tissue nasion, and the most anterior aspect of the cornea—have been successfully employed to define the anteroposterior position of a coronal plane of reference.

When assessing the facial profile, the patient should be in standard anatomical alignment (*i.e.*, head in the NHP), with the clinician observing from the side. While in this position, the clinician imagines a coronal plane of reference—a plane that can be tangential to soft-tissue glabella, soft-tissue nasion, or the anterior surface of the cornea. Concurrently, the clinician infers the anteroposterior position of the jaws by assessing the position of the lips and chin in relation to this paracoronal plane (Figure 5).

No perfect reference plane exists for determining the anteroposterior position of the jaws. Nasion can be obscured in Asian patients, as it is commonly located posterior to the cornea; glabella can be distorted in frontal bossing; and distances from the cornea are difficult to gauge clinically. Notwithstanding these limitations, our clinical impressions are reliable because our brains have the innate ability to discern the correct anteroposterior position.

VERTICAL

Clinically, one determines the vertical position of the maxilla by measuring the *rest-incisal-show* and the *smile-dento-gingival-show* (Figure 6). Rest-incisal-show is the amount of upper incisor that is exposed when the lips are relaxed. It is the vertical distance from the upper lip *stomion* to the maxillary *incisal midpoint*. *Stomion* is the midpoint of the free-edge of a lip, upper or lower. The *incisal midpoint* is the point at the intersection of the dental midline and the arc defined by the incisal edges (Figure 7). It represents the middle of the dental arch. When the maxillary *incisal midpoint* is below stomion (baseline), the rest-incisal-show is positive; when above, it is negative. Rest-incisal-show should be measured at the *incisal midpoint* rather than at other points on the incisal edges because, when the maxilla is canted, incisal show varies at each location (Figure 7).

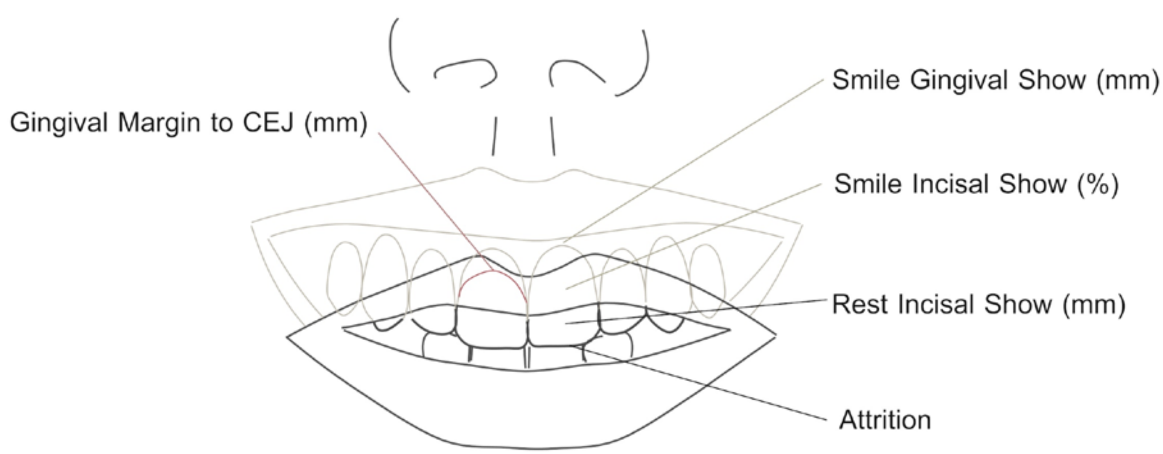


Figure 6. Assessing vertical maxillary position.

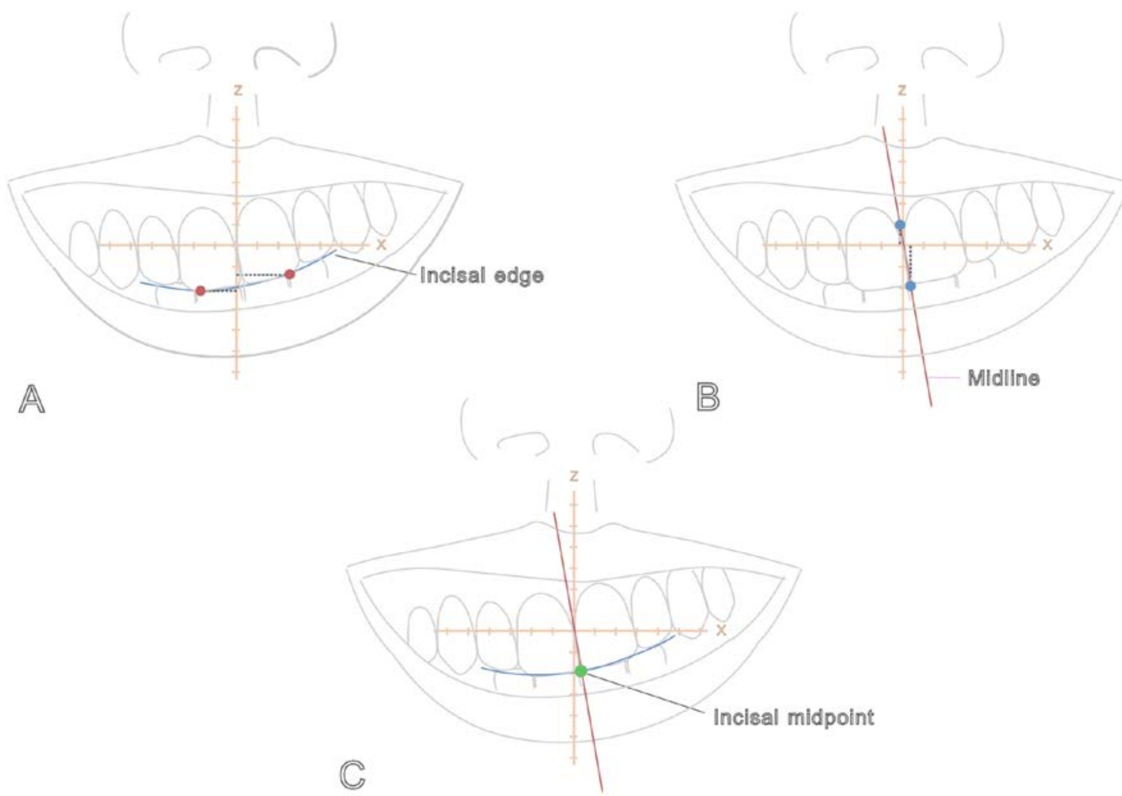


Figure 7. Incisal midpoint.

Based on the above referenced assessments, one classifies the occlusion into neutrocclusion, distocclusion, or mesiocclusion. In neutrocclusion, the molar and canine relationships are Class I and the overjet is normal. In distocclusion, the molar and canine relationships are Class II and the overjet is either greater than normal (Division 1) or normal (Division 2). In mesiocclusion, the molar and canine relationships are Class III and the overjet is smaller than normal, usually negative.

Rest-incisal-show should be measured on an upright patient, as it can increase when the patient is supine (Figure 8). Additionally, the eyes of the examiner should be level with the patient's lips, as looking from above hides the teeth, and viewing from below exposes them. Negative incisal shows are difficult to measure. To overcome this challenge, the authors place a piece of wax on the lingual surfaces of the upper incisors, extending it downward below the lip. Subsequently, the clinician asks the patient to relax his lips and marks (on the wax) the position of the upper lip stomion. Finally, the clinician pulls the upper lip up and, with a caliper, measures the distance from the mark to the incisal midpoint (Figure 9). Some patients may have incisal attrition, which is the erosion of the incisal edges due to grinding. In this situation, the examiner should add the amount of tissue loss to the measurement.

To determine the vertical position of the maxilla, the examiner compares the patient's *rest-incisal-show* with normal values. Gender, age, ethnicity, and the length of the upper lip influence these values.[17] Female patients have more incisal show than males. Incisal show also decreases with age.[17, 18] Caucasians tend to have more incisal show than patients of other ethnicities.[17] Patients with short upper lips tend to have more incisal show than those with longer lips.[17] For example, a 5mm incisal show is considered

Figure 8. Rest-incisal-show changes with patient position. A) The patient is upright. B) The patient is supine.

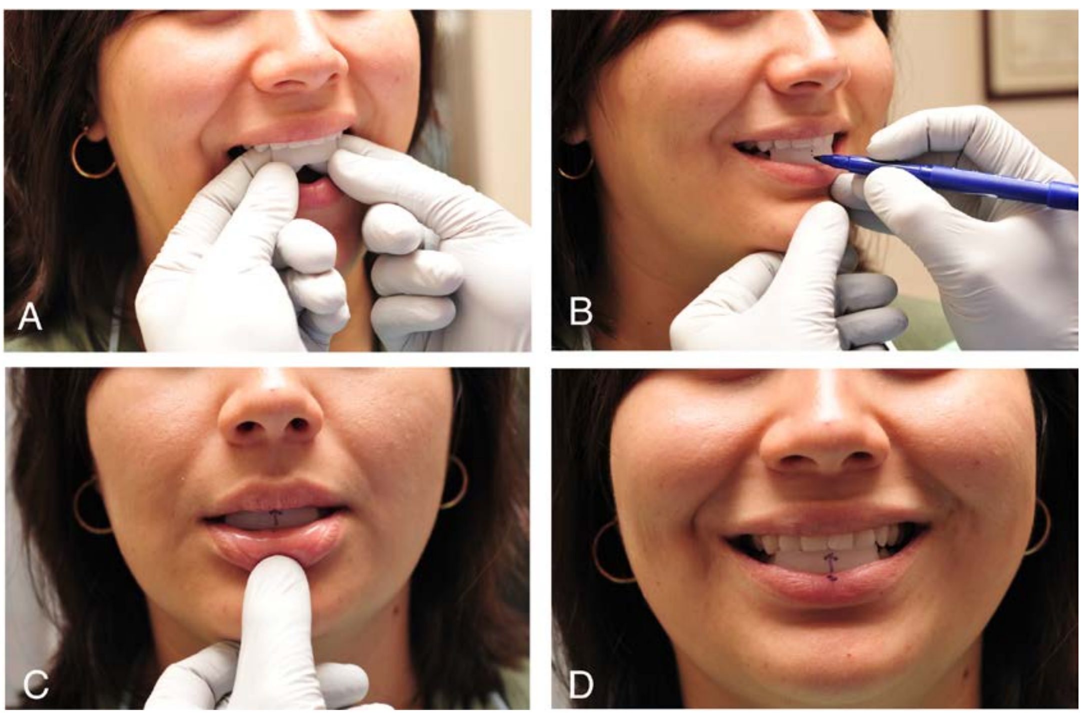


Figure 9. Measuring negative rest-incisal-show. A) Wax is placed behind the upper incisors. B) The dental midline is extended into the wax. C) The lips are placed in reposed and the position of the upper lip stomion is marked of the wax. D) The distance from the stomion to the upper incisal midpoint is measured.

normal in a teenage girl with a short upper lip, while a 1.5 mm incisal show is considered normal in a 60-year-old male. Patients with a negative incisal show are deemed to have *deficient maxillary downward displacement*, and patients with incisal shows above the normal range for their particular gender, age, ethnicity, and length of upper lip are deemed to have *excessive maxillary downward displacement*.

As stated previously, smile-dento-gingival-show is also used to determine the vertical position of the maxilla. Smile-dento-gingival-show is the amount of central incisor and labial gingiva displayed when smiling. Tooth show is measured as a percent of its height, while gingival show is measured in millimeters. While smiling, most patients with normal vertical maxillary position display 100% of their incisors[19] and up to 2 mm of gum. Patients with superiorly positioned maxillae show less than 100% of their incisors, whereas patients with inferiorly positioned maxillae display an excessive amount of gum.[20] Yet the amount of tooth and gum displayed during the process of smiling is not only related to the vertical position of the maxilla, it is also associated with lip animation and passive dental eruption.

Too much or too little tooth and gum displayed during smiling may be a consequence of abnormal lip animation.[21, 22] A hyperactive smile—caused by hyperactive smile muscles—produces a "gummy" smile; a hypoactive or weak smile, results in significantly less tooth display. Hyperactive smile is diagnosed when the gingival-show is large, the rest-incisal-show is normal, and passive dental eruption (next paragraph) is normal. A hypoactive smile is diagnosed when the smile-tooth-display is small and the rest-incisal-show is normal.

Tooth eruption can consist of active and passive phases. Active eruption is the movement of teeth toward the occlusal plane, while passive eruption is related to the exposure of teeth through apical migration of the gingiva. When passive eruption does not progress, the result is a dental crown that appears short because of the presence of excess gingiva covering the enamel. Clinically, the most obvious sign of delayed passive eruption is a short clinical crown; also, sulcus depths, from the gingival margin to the cement-enamel-junction, are large (over 3 mm).[1] Patients with delayed passive eruption may have large smile-gingival-shows, despite normal vertical maxillary position. In this scenario, the smile-gingival-show is large, but the rest-incisal-show is small or normal.

Transverse

Clinically, transverse jaw position is established by measuring the distance between middle landmarks and the median plane. In the maxilla, one solely measures the position of the upper incisal midpoint. In the mandible, however, one measures the position of two points: the lower incisal midpoint and soft-tissue pogonion (*i.e.*, the most prominent point of the soft-tissue chin). The transverse position should be measured at the incisal midpoint points rather than any other point on the dental midline because when the jaws are canted, measurements vary with point position (Figure 7). Also, when assessing the transverse position of the mandible, the mandible must be in centric relationship—the mandibular position in which the condyles are fully seated within the glenoid fossae.

Clinical Assessment of Jaw Orientation

During the physical examination, the pitch, roll, and yaw of the jaws is assessed in relation to the frame of reference of the entire face—the system defined by the median, axial, and coronal planes.[7] Pitch is difficult to measure clinically and is best assessed with radiographic cephalometry. Roll and yaw are related to symmetry and are discussed in the following section.

Clinical Assessment of Jaw Symmetry

The plane of symmetry of the face is the median plane. Midline landmarks like glabella, nasion, subnasale, incisal midpoint, and pogonion should lie on the median plane. Bilateral structures like the eyes, ears, and gonial angles should be aligned on each side of the median plane, as mirror images.

During the physical examination, one infers the symmetry of the jaws by inspecting the face and examining the dentition. To assess facial symmetry, the examiner must first stand in front of the patient, looking at his/her face. While doing this, he should mentally visualize the median plane and appraise two factors. First, it must be determined if the midline structures are on the median plane; second, one must establish whether bilateral structures are positioned as mirror images in relation to this plane. The examiner should also inspect the face from above and below to ascertain if bilateral structures have the same anteroposterior position. All deviations should be measured and recorded (Figure 10).

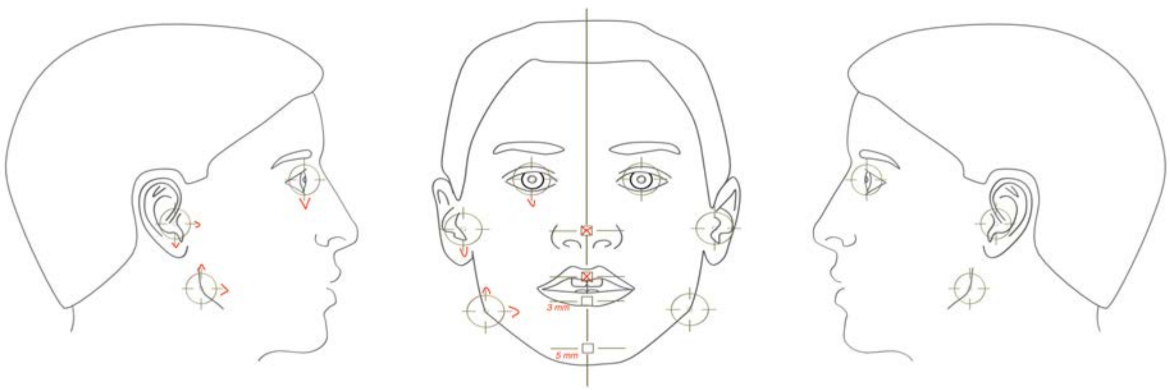


Figure 10. Clinical assessment of facial asymmetry.

Clinicians also determine symmetric jaw alignment by examining the dentition. When the jaws are symmetrically aligned, the upper and lower incisal midpoints lie on the median facial plane. Also, corresponding right and left teeth have the same vertical position and the same horizontal distance to the median and coronal planes.

Transverse deviations of the upper and lower incisal midpoints should be measured and recorded. The roll of the maxilla can be clinically determined by measuring, with a Boley gauge, the vertical distances from each medial canthus to the ipsilateral maxillary teeth (Figure 11). Right-left differences that are consistent through the arch indicate canting (abnormal roll) of the upper jaw. These measurements should be interpreted with caution as they can be affected by local dental irregularities, vertical eye dystopia, and yaw malrotation of the upper jaw.

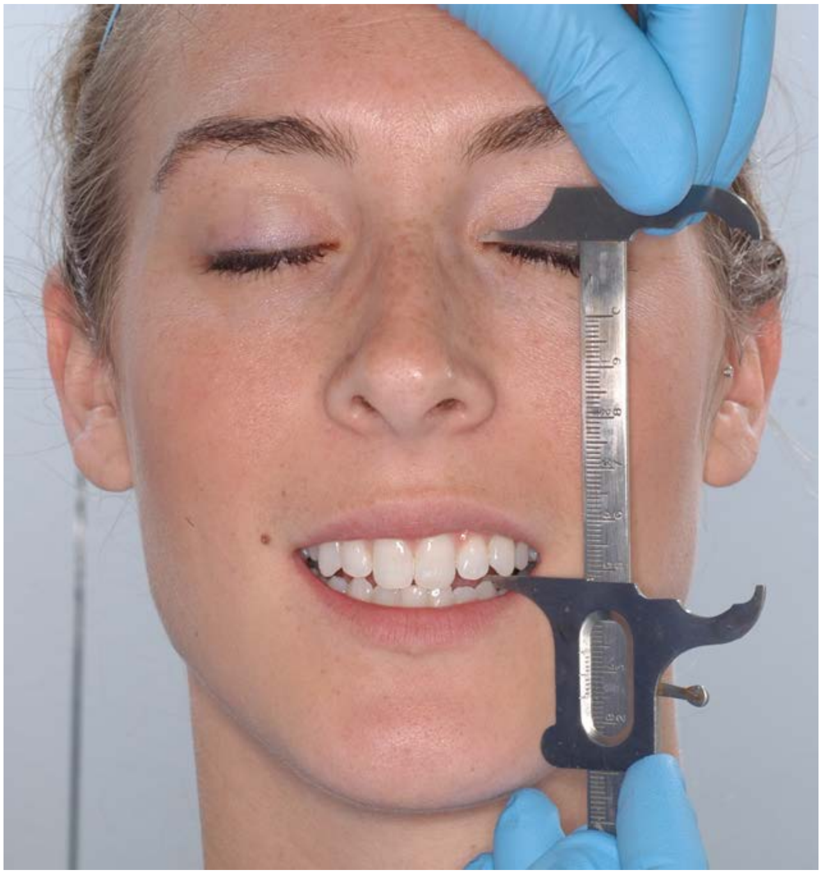


Figure 11. Clinically, maxillary roll (cant) can be quantified by measuring the vertical distance from the medial canthi to the upper teeth.

Diagnostic Test

Jaw deformities cannot be fully assessed clinically. Hence, there is a need to gather additional information derived from diagnostic tests that may include imaging studies, radiographic cephalometry, and/or dental model analyses.

Radiographic Cephalometry

The literal meaning of cephalometry is head measurement, and such measurements can be taken both clinically and radiographically. The term *radiographic cephalometry* is used to describe head measurements taken from an X-ray image. Traditionally, radiographic cephalometry has been performed on standardized two-dimensional X-ray images called cephalograms. In this chapter, however, the authors discuss three-dimensional (3D) radiographic cephalometry, a relatively new methodology that aims to quantify facial form by using 3D data derived from computed tomography (CT).

Basic Principles of 3D Cephalometry

Cephalometry requires knowledge in 3 fields: biology, geometry, and statistics. In this section, the authors review the geometric principles of 3D cephalometry. Although some of the geometry is challenging, one should make an effort to learn it, as it is invaluable.

In orthognathic surgery, clinicians use cephalometry to determine the configuration of the jaws. Like other objects, jaws have four basic geometric properties: size, position, orientation, and shape. In addition, they have a fifth property: reflection symmetry. In the following sections, the authors describe how to measure each of these parameters in 3D.

Size Measurements

Size is an intrinsic property of an object, and is independent of the space it occupies. One can measure size using linear measurements (*e.g.*, length, width, and height), areas, or volumes. In 3D cephalometry, the simplest size measurements are length, width, and height; they are calculated as the distance between 2 points (landmarks) located in 3D space. For example, one can measure the width of the maxilla by calculating the distance between palatal cusps of the first molars.

Position Measurements

Position refers to *point* location in space. With 3D cephalometry, one is interested in determining the location of the jaws. Yet the jaws are complex three-dimensional objects composed by thousands of points, each one with a different position; therefore, to determine jaw location, one is tasked with selecting a single point to represent the entire jaw. However, because there is no perfect point, in practice one must use several. In the maxilla, clinicians use the anterior nasal spine (ANS), point A, and upper incisal midpoint. The anterior nasal spine represents the basal bone of the maxilla, point A represents the apical base, and the upper incisal midpoint represents the dentition. In the mandible, clinicians use pogonion, point B, and the lower incisal midpoint. Pogonion represents the basal mandible, point B the apical base, and the lower incisal midpoint, the dentition.

Measuring position in one, two, and three dimensions requires one, two, and three numbers, respectively. Thus, any system that measures jaw position in 3D must utilize three numbers. In general, one can measure 3D position using one of three systems: Cartesian, cylindrical, and spherical. Cartesian systems use three distances. Cylindrical systems use two distances and one angle. Spherical systems use one distance and two angles. Because spherical systems are not used in cephalometry, they will not be described here.

A 3D Cartesian-coordinate-system consists of three perpendicular axes (number lines) that cross one another at zero. The transverse axis is x, the anteroposterior axis is y, and the vertical axis is z. Each pair of axes forms a reference plane. In this system, one locates any point by measuring the distances from that point to each reference plane. Location is expressed using 3 coordinates (x, y, z).

Using a Cartesian system in 3D cephalometry is straightforward. The anteroposterior, vertical, and transverse positions of any landmark are expressed as (x, y, z) coordinates in a standard anatomical reference system. Relative position between two landmarks is easily calculated using arithmetic. For example, if the anteroposterior coordinate of point A is 62, and the anteroposterior coordinate of nasion is 60. Point A is said to be 2 mm in front of Nasion (62-60=2).

A cylindrical system is an extension of the two-dimensional polar system; it is, therefore, easier to learn a cylindrical system by first learning the polar system. A polar system resides on a plane consisting of a fixed point—the *pole*—and a ray—the *polar axis*. From the pole, the polar axis points in a fixed direction.

In this system, one determines the position of any point by first drawing a line segment from the point one is locating to the pole; this line segment is called the *radius*. One then measures the length of the radius (r), and the angle between the radius and the polar axis (θ). The position is expressed using two coordinates (r, θ) (Figure 12).

A cylindrical system adds one axis to the polar system. This axis, called the *cylindrical axis*, is perpendicular to the plane of the polar system and passes through the pole. In a cylindrical system, one measures the location of any point in 3D space by first projecting the point on the plane of the polar system. On this plane, one then establishes the position of the point projection using standard 2D polar coordinates (r, θ). The third coordinate is the distance from the point one is locating to the plane of the polar system.

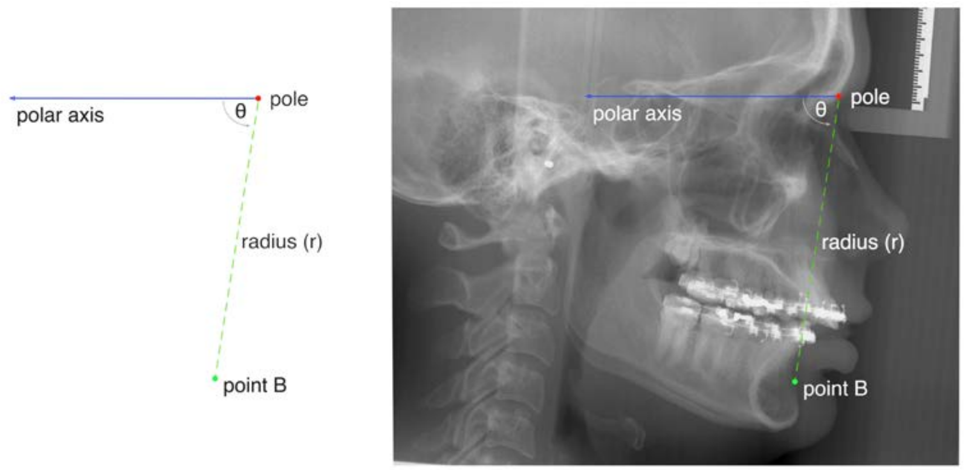


Figure 12. Cephalometric assessment of jaw position: two-dimensional polar system.

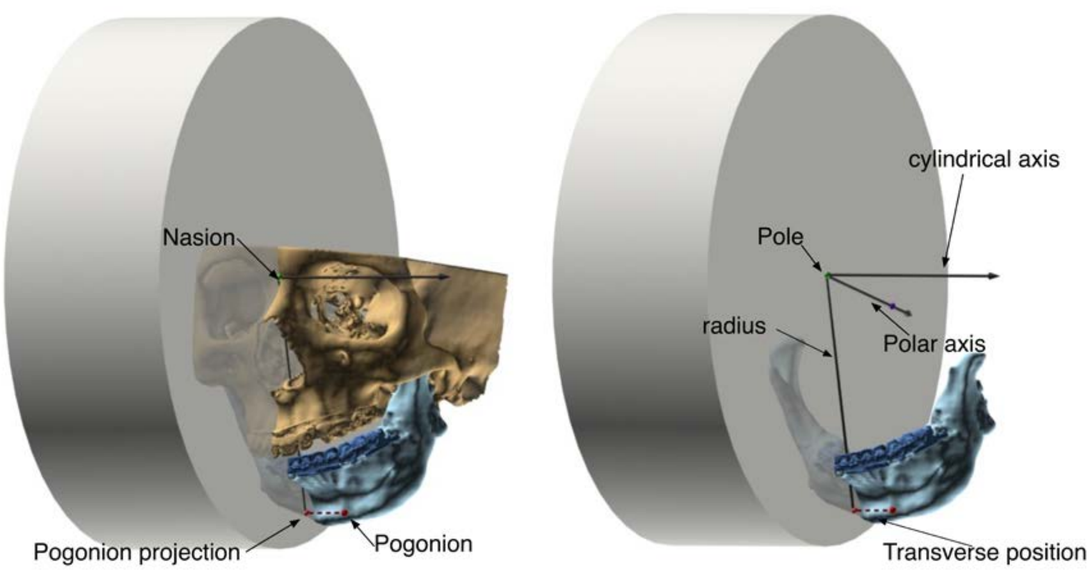


Figure 13. Cephalometric assessment of jaw position: three-dimensional cylindrical system.

Figure 13 illustrates how cylindrical systems work. In this example, the point B position is being measured in relation to sella-nasion (the anterior cranial base). The origin of the coordinate system (the pole) is nasion. The polar axis is the ray that originates on nasion, pointing at sella. The cylindrical axis is perpendicular to the median plane, crossing nasion. One establishes the location of point B by first projecting this point on the median plane, then by measuring r and θ on the plane. The radius (r) is the distance from the point-B-projection to nasion. Theta (θ) is the familiar SNB—the angle between sella-nasion (SN) and the point-B-projection. The last coordinate (transverse position) is the positive or negative distance between point B and the median plane.

ORIENTATION MEASUREMENTS

Orientation is defined as the imaginary rotations required to move an object from a reference alignment to its current position. Let us clarify with an example. Figure 14 shows an airplane taking-off. Independent of its position or orientation in space, the airplane has a top, a bottom, a front, a back, a right side, and a left side. These intrinsic features can be used to draw three perpendicular axes: anteroposterior, top-bottom, and right-left (shown in the figure in light colors); combined, they form the airplane's *object coordinate system*. As the term implies, object coordinate systems belong to objects. They are determined by the configuration of objects and, as such, they translate and rotate with them.

To continue, the space around the airplane also has a frame of reference. Like the airplane's frame of reference, it also has three axes. In aeronautics, the axes of space are up-down, east-west, and north-south; combined, they make the *world coordinate system*. Figure 14 shows the world coordinate system at the beginning of the runway, in darker colors.

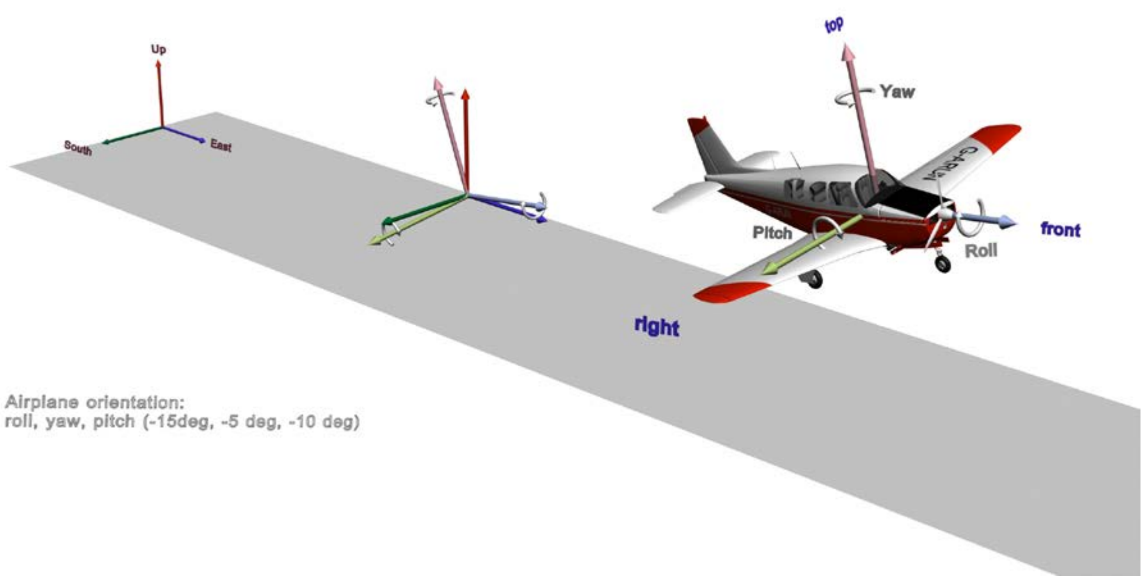


Figure 14. Measuring orientation.

Gauging orientation, like measuring position, is always relative. To calculate it, one must decide on a reference orientation. For example, in this scenario the airplane's orientation is being assessed in relation to the world. To measure orientation, one superimposes the origin of the object coordinate system (the airplane's) onto the origin of the reference coordinate system (the world's). Once this position has been established, pitch, roll, and yaw are measured.

Similarly, to measure jaw orientation, one compares the orientation of each jaw with the orientation of the whole head. For this, a computer program automatically constructs coordinate systems for each jaw (using a principal component analysis) and compares them with the coordinate system of the entire head (Figure 15). The order in which the software measures pitch, roll, and yaw is essential; these angles are not commutative. This means that the order in which they are measured affects the values derived. *The authors recommend measuring yaw, roll, and then pitch, as employing this order is clinically relevant.*

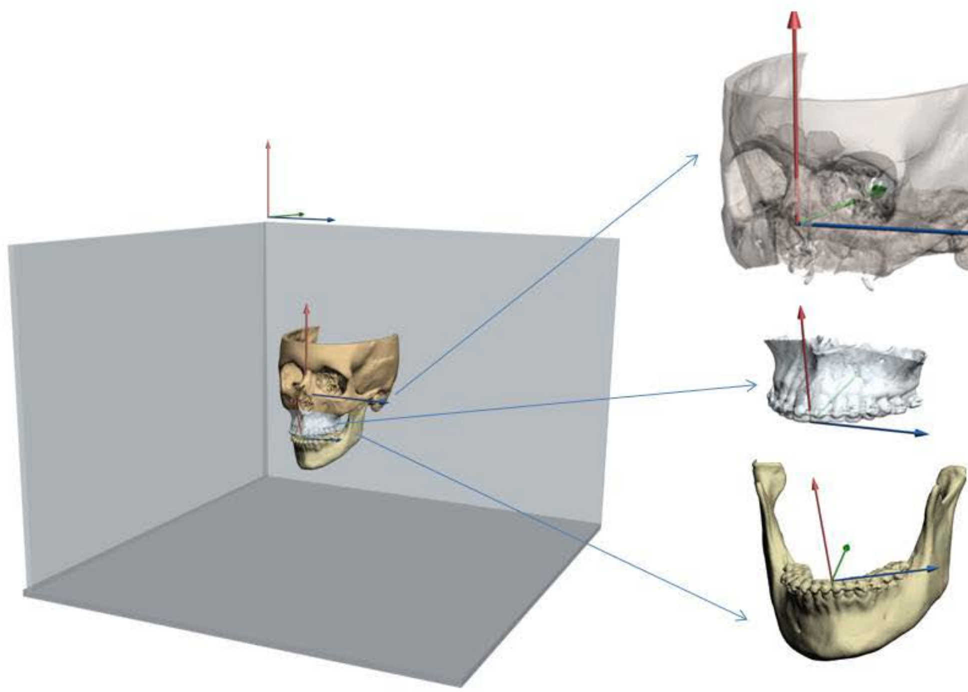


Figure 15. Measuring jaw orientation.

Shape Measurements

Shape is the geometric property of an object that is *not size*, *not position*, and *not orientation*.[5, 23] As one can see, shape is defined by what it is not, rather than by what it is. When comparing two objects, shape is the characteristic that remains after objects have been scaled to the same size, placed at the same position, and rotated to the best possible alignment.

Figure 16 illustrates this concept. The figure depicts two mandibles: the top one (orange) is the average mandible; the lower one (blue) is deformed. These mandibles differ in size, position, orientation, and shape. To appreciate the differences in shape, it is necessary to first scale both mandibles to the same size. Next, one must place both mandibles in the same position. Finally, the deformed mandible is rotated until it is best aligned with the average mandible—the target. This process is known as Procrustes superimposition.[5]

As one can see in the example: after the differences in size, position, and orientation have been removed, the deformed mandible has a distorted shape. Specifically, it has an obtuse gonial angle, and a relatively shorter ramus.

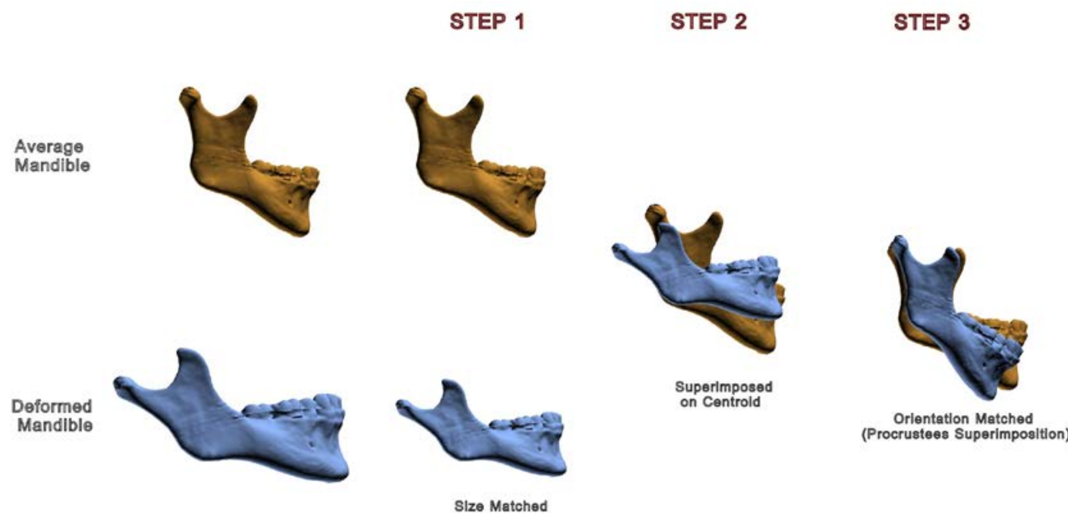


Figure 16. Shape analysis: Procrustes superimposition.

SYMMETRY MEASUREMENTS

As mentioned previously, there are two factors related to symmetry. One is object symmetry, the other symmetric alignment. Object symmetry can be measured using a Procrustes Analysis,[5, 23-27] a mathematical method that detects shape differences among similar objects. The analysis begins by superimposing objects *optimally*. For the superimposition, the objects are first translated to the same location. Next, they are scaled to the same size. Then, one of them is kept static as a target, while the other is rotated until the distances between corresponding landmarks located in both objects become minimal.

At times, rather than looking for differences in *shape*, one is interested in comparing *forms*—form being the combination of size and shape. To compare forms, a Procrustes superimposition does not scale the objects to the same size. This is the type of Procrustes superimposition one uses to assess symmetry.

A Procrustes Analysis of Symmetry begins by dividing the form of a facial unit (*e.g.*, the mandible) into two half-forms: right and left (Figure 17A). To divide the form, the landmarks of the whole form are divided into 2 groups. The right set contains the coordinates of all the right landmarks as well as all the midline landmarks (Figure 17B); the left set contains the coordinates of all the left landmarks and the midline landmarks (Figure 17C). We then use each group of landmarks to create 2 half-forms.[5, 23, 27]

Next, using a series of transformations, we superimpose the 2 half-forms. However, before starting, we must pick one half-form to be the object of the transformations, with the other as the target. Which half-form (right or left) becomes the target is inconsequential.

The first transformation reflects (flips) one of the half-forms around its sagittal plane, creating a mirror image (Figure 17D). This operation makes the half-forms comparable. The second transformation centers both half-forms on a Cartesian coordinate system. To center the half-forms, we first determine the centroid of each. Then, we translate both forms, so that their centroids are on the origin [coordinates

(0, 0)] of the Cartesian system. The third transformation rotates the object half-form around its centroid until the form is aligned to the target. Alignment is reached when sum of all the distances between corresponding landmarks of the right and the left half-forms is minimal (Figure 17E).

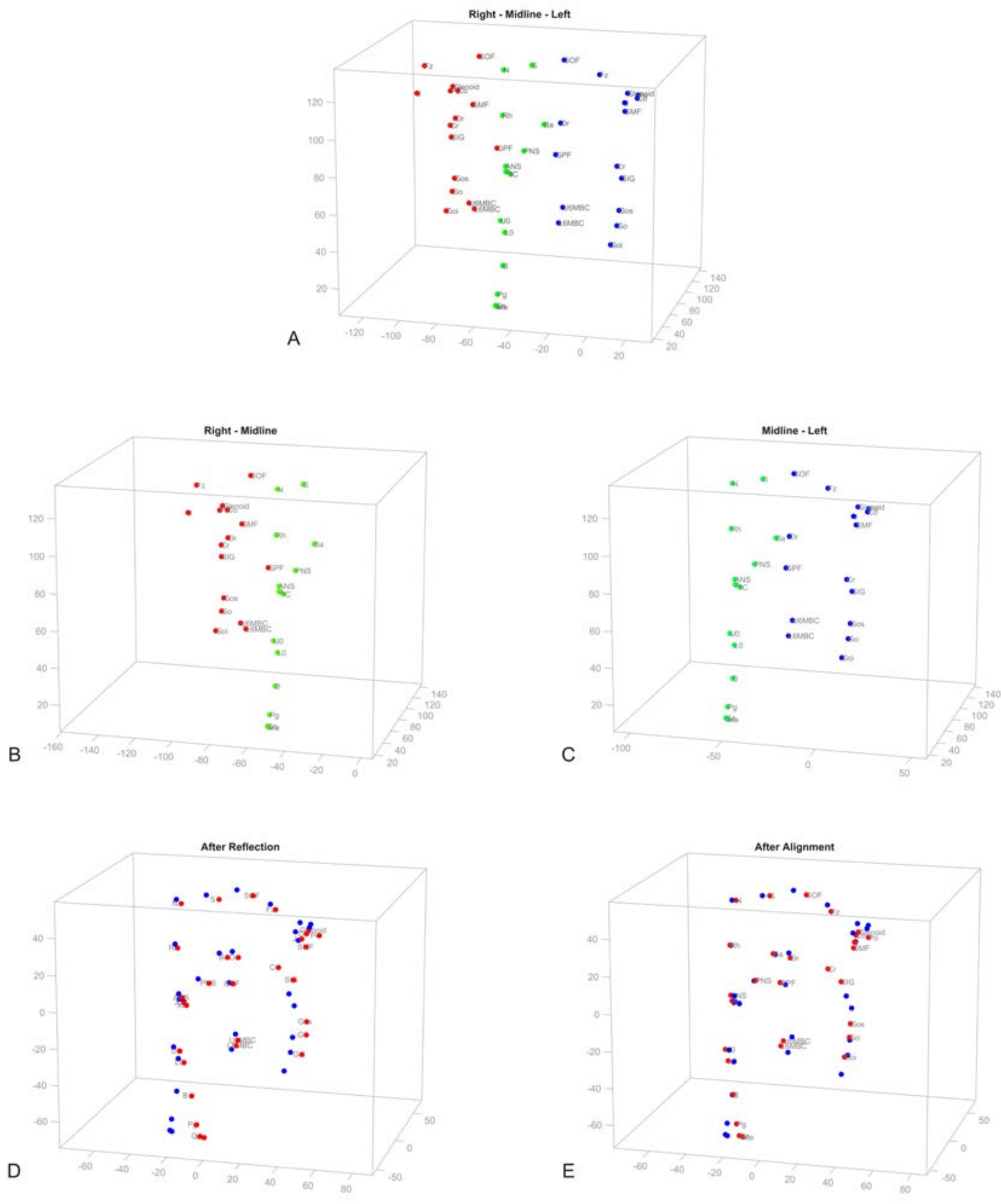


Figure 17. Procrustes Analysis of Symmetry. **A)** A mandible has three groups of landmarks, right, middle and left. The landmarks of the whole mandible are divided into 2 groups to create 2 half-forms: **B)** the right set contains the coordinates of all the right landmarks and all the midline landmarks; **C)** the left set contains the coordinates of all the left landmarks and the midline landmarks. **D)** The right set is reflected to the left, creating a mirror image. **E)** The reflected right set is iteratively aligned to the left set till the sum of all the distances between corresponding landmarks of the right and the left half-forms is minimal.

To quantify the degree of asymmetry of each landmark, we measure the (partial) Procrustes distances between analogous right and left landmarks. These distances are directly proportional to the degree of asymmetry. Thus, they work well for our estimations.

Unfortunately, Procrustes superimposition is susceptible to the Pinocchio effect[5], a phenomenon that occurs when outlier landmarks sway the alignment of a form, magnifying the Procrustes distances of other, less displaced, landmarks. Fortunately, we can curtail the Pinocchio effect generated by the most displaced landmarks by decreasing their weight on successive Procrustes superimpositions.

Figure 18 shows an example of using a Weighted Procrustes Analysis of Symmetry to measure the asymmetry of a mandible.

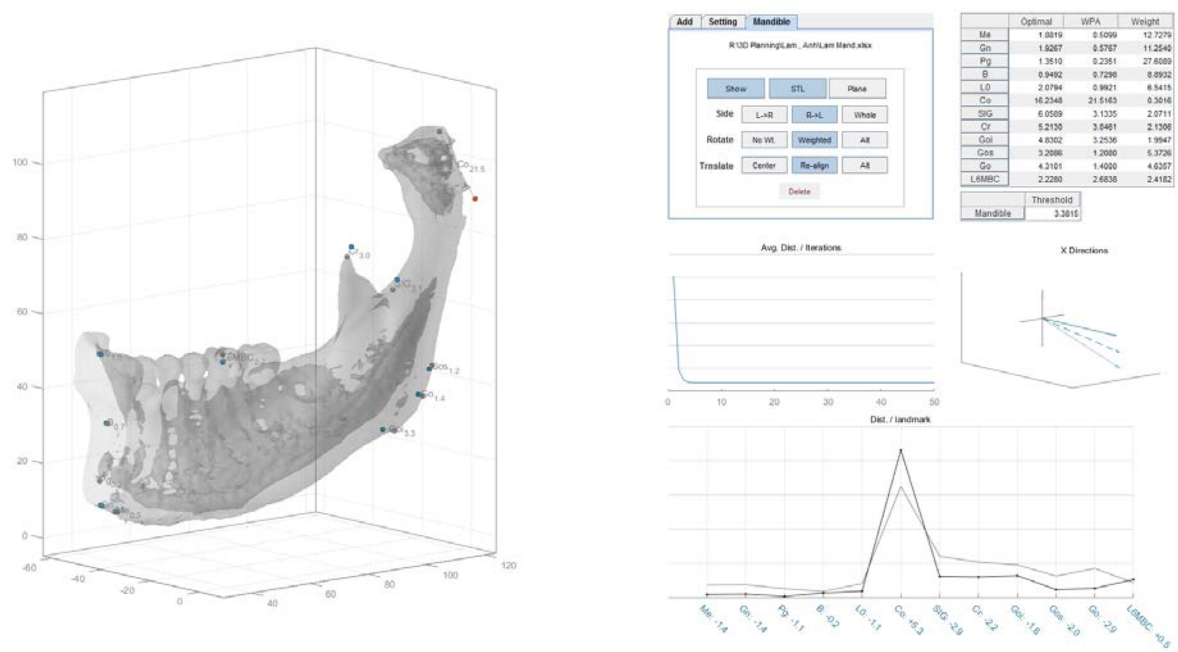


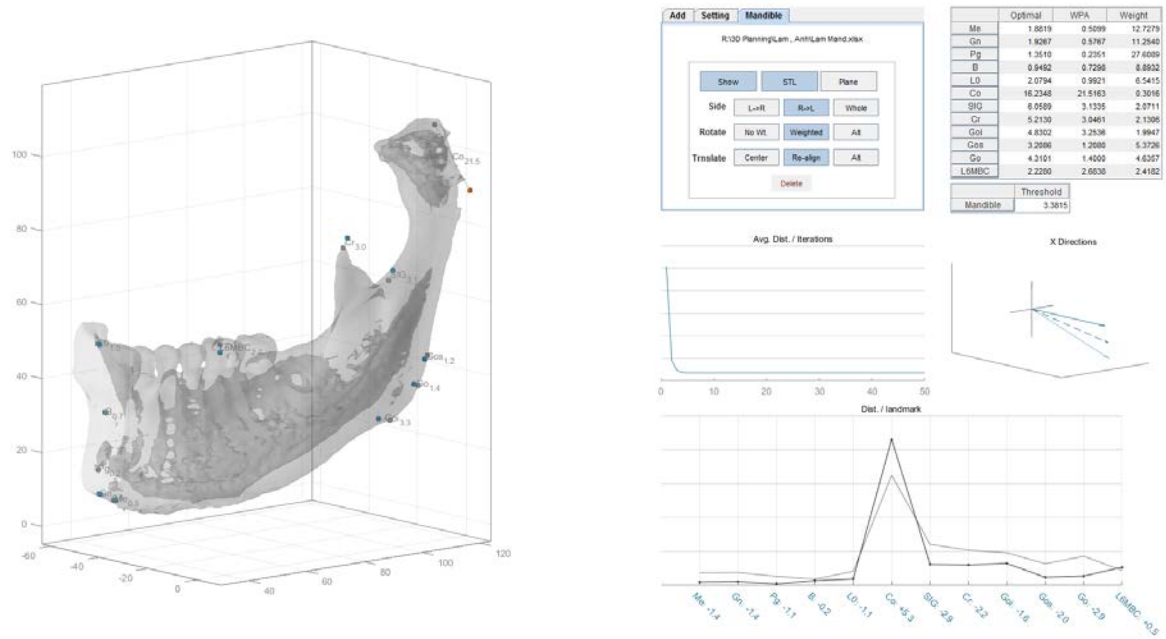
Figure 18. An example of using Weighted Procrustes Analysis of Symmetry to measure the asymmetry of a mandible.

After calculating object symmetry, one measures symmetric alignment by calculating the movements (transformations) necessary to align the jaws to the median plane of the face. Here, three transformations are needed. They are transverse translation, roll, and yaw. Transverse translation places the incisal midpoint on the median plane. Roll rotates the jaws around the incisal midpoint until the right and left landmarks are vertically aligned. Yaw rotates the jaws around the incisal midpoint, minimizing distance differences between corresponding bilateral landmarks and the vertical reference planes—coronal and median. Ideal values for transverse position, yaw, and roll are zero.

GATENO-XIA 3D CEPHALOMETRIC ANALYSIS

The 3D cephalometric analysis of the authors is a grid (Table 2).[7, 25] In each row, one assesses a different geometric property. Five properties are assessed: object symmetry, shape, size, position, orientation, and symmetric alignment. The columns belong to the individual facial units (*e.g.*, maxilla and mandible).

In the first part of the analysis, *object symmetry*, one determines the intrinsic symmetry of each jaw. In the second part, *shape*, one measures the shape of the jaws using a 3D Procrustes analysis. In the third part, *size,* one measures the dimensions of each jaw: length, width, and height. In the fourth part of the analysis, *position*, one measures the location of the jaws on each facial axis—anteroposterior, vertical, and transverse. Depending on the preference of the clinician, position can be measured using a 3D Cartesian system or a cylindrical system. In the fifth and final part of the study, *orientation*, one measures the orientation of the jaws (*i.e*



., yaw, roll, and pitch). *Symmetric alignment* is a composite of three measurements: transverse position, yaw, and roll.

Table 2: Gateno-Xia 3D Cephalometric Analysis

<table>
<tr><td colspan="3" rowspan="2"></td><td>Maxilla</td><td colspan="2">Mandible</td></tr>
<tr><td></td><td>Whole</td><td>Chin</td></tr>
<tr><td colspan="3">Object Symmetry</td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Shape</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Size</td><td colspan="2">Length</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Width</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Height</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Position</td><td colspan="2">Anteroposterior</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Vertical</td><td></td><td></td><td></td></tr>
<tr><td>Transverse</td><td rowspan="3">Symmetric Alignment</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Orientation</td><td>Yaw</td><td></td><td></td><td></td></tr>
<tr><td>Roll</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Pitch</td><td></td><td></td><td></td></tr>
</table>

Dental Model Analysis

A dental model analysis is an essential component in the evaluation of patients requiring orthognathic surgery. It is done at least twice: before orthodontics and prior to surgery. The first analysis—the initial dental model analysis—guides orthodontic treatment; the second—the progress dental model analysis—establishes readiness for surgery.

In orthognathic surgery, surgeons and orthodontists collaborate to normalize the jawbones and the occlusion. In the first stage of treatment, an orthodontist aligns the upper and lower teeth to their corresponding jaw, creating normal dental arches. A surgeon then aligns the arches with one other during surgery. The orthodontist's task is complex. He/she must coordinate the dental arches so that they can be placed in normal intercuspation at surgery. Coordination of dental arches entails giving the dental arches (upper and lower) corresponding forms. An initial dental model analysis shows the clinician how the pretreatment form deviates from the target, which is essential to planning correction.

An initial dental model analysis includes the following:

- Analyses of shape
  - Arch shape correspondence
  - Dental alignment
  - Dental leveling
  - Curve of Spee
  - Buccolingual inclinations
- Analyses of size
  - Spacing
  - Arch width
  - Bolton assessment

A dental model analysis has multiple components, which the authors have classified into two groups: Appraisals of *shape* and appraisals of *size*. The first appraisal of shape is *arch shape correspondence*. For teeth to fit into a normal occlusion, the shapes of the upper and lower dental arches must be similar. This is called arch shape correspondence. To assess it, one looks at the occlusal surfaces of both models simultaneously, mentally comparing the shapes of both arches. Dissimilar shapes are a problem; for instance, a "U" shaped lower arch will not fit a "V" shaped upper arch, and a square lower arch will not fit a "U" shaped upper arch.

The second appraisal of shape, evaluates *dental alignment*. With perfect alignment, the edges of the incisors and the buccal-cusp-ridges of canines, premolars, and molars make a catenary arch. Misalignment occurs when the teeth are not aligned in an arch, because of malrotation, displacement, or tipping.

The third shape appraisal evaluates *dental leveling*. Leveling refers to the vertical position of teeth in relation to the occlusal plane. The occlusal surfaces of all teeth should be on the plane.

The fourth shape appraisal assesses the *curve of Spee*.[28] The curve of Spee is the up-down curvature of the occlusal plane. It starts in the canine and extends back, to the last molar. An ideal curve of Spee is flat or has minimal upward concavity.[29]

The fifth and final shape assessment appraises the *buccolingual inclination of posterior teeth*. In the mandible, the lingual cusps should be 1 mm lower than the buccal. In the maxilla, the buccal cusps should be 1 mm higher than the palatal. Buccolingual inclination is assessed with a straightedge. In the mandible, the straightedge is placed on corresponding buccal cusps and the gap between the tool and the lingual cusps is measured. In the maxilla, the straightedge is placed on the palatal cusps and the gap between the instrument and the buccal cusps is measured.

The next group of measurements appraises size. Among them is *spacing*, which is a comparison between the space available for the alignment of teeth and the space required. In the first step, one calculates the available space: the arch perimeter from one first molar to the other. In the second step, an examiner measures the space needed, which is the sum of the widths of individual teeth—premolars, canines, and incisors.[13]

Another essential component of the size appraisal is *arch width*, which is measured at the first molars. In an ideal Class I occlusion, the mesiopalatal cusps of the upper first molars occlude with the distal fossae of the lower first molars. Thus, the distance between the mesiopalatal cusps of the maxillary first molars should be the same as the distance between the distal fossae of the mandibular first molars. A discrepancy between these measurements may reveal an underlying apical-base deformity.

The final measure is the *Bolton assessment*. This analysis originated from the observation that, in order to obtain the proper interdigitation and arch coordination in a Class I relationship, the width of the lower teeth must be proportional to the width of the upper teeth. Bolton discovered that a Class I canine occlusion is only possible when the upper and lower anterior teeth have a specific proportion. The sum of the widths of the lower anterior teeth must be 77% of the sum of the widths of the upper anterior teeth.[13] Failure to account for a Bolton discrepancy commonly results in a lack of arch coordination.

Planning Treatment

Jaw deformities can be corrected using different types of operations. Deformities of jaw size, jaw position, jaw orientation, jaw shape, or jaw symmetry can be corrected with *orthognathic surgery* or through *distraction osteogenesis*. Deformities of jaw completeness require reconstructive surgery.

In this online resource, we present our approach to planning orthognathic surgery and distraction.

Planning Orthognathic Surgery

Orthognathic is a compound word of Greek origin (*ortho*- straight; -*gnathous* jaw) meaning straight jaw. Thus, *orthognathic surgery* refers to surgery that is performed to *straighten a jaw*. It entails cutting a jaw and relocating at least one of its segments

Orthognathic surgical treatment has three well-defined stages: presurgical orthodontics, surgery, and postsurgical orthodontics. In the first stage, an orthodontist aligns and levels the teeth, removes unwanted compensations, and coordinates the dental arches. In the second stage, surgery takes place. In the final stage, an orthodontist completes the orthodontic movements.

Treatment planning is a process used to determine the particulars of treatment. Formal treatment planning is required at two different times (Figure 19): prior to orthodontic treatment (the *initial treatment plan*) and before surgery (the *surgical treatment plan*).

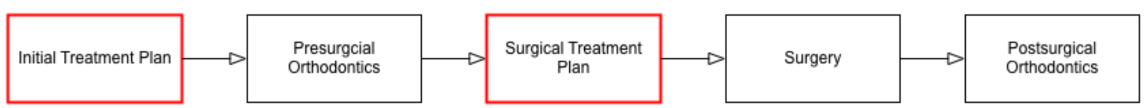


Figure 19. Stages for orthognathic surgery.

Initial Treatment Plan

The initial treatment plan is completed before the orthodontic treatment commences. The main goal of initial planning is to develop an orthodontic plan. The orthodontist and surgeon should agree on a tentative surgical plan. This plan is crucial, as it influences important orthodontic decisions; for example, dental extractions, the removal of dental compensations, and the creation of interdental spaces for osteotomies.

Surgical Treatment Plan

Before surgery is planned, the surgeon must determine whether the patient is ready for surgery. This entails confirming that the goals of presurgical orthodontics have been met and that the patient's health has been optimized to ensure the lowest possible surgical risk.

Surgeons obtain *progress-dental-models* to determine that the goals of presurgical orthodontics have been met. They hand-articulate the models in Class I occlusion to confirm that good occlusion is achievable. Good occlusion can be achieved when:

- Dental compensations have been eliminated

- The teeth are well aligned, forming a smooth arch
- The shape and size of the upper and lower dental arches match
- Adjacent marginal ridges are leveled
- Interproximal spaces are closed (unless spacing is needed to compensate for a discrepancy in tooth size)
- The curve of Spee is flat or minimal
- The labiolingual inclination of posterior teeth is normal
- The incisal overjet and overbite are normal
- The tooth size discrepancies (Bolton) have been dealt with
- Occlusal contacts are maximized

If good intercuspation is observed and the risks of surgery are acceptable, the patient is ready for surgery.

Occasionally, good intercuspation cannot be achieved because of the presence of an *apical base* deformity. The *apical base* is the part of the jawbones located around the apices of teeth, and it determines the position of the dental roots. Because dental roots should not be moved outside the bone, maximal intercuspation cannot be achieved when the apical bases are deformed. For example, when the maxillary apical base is narrow the posterior teeth will end in crossbite, despite adequate presurgical orthodontics. In such cases, the maxilla must be segmented—separated into two or more tooth-bearing bone segments—so that it can be expanded.

If good intercuspation cannot be achieved because of an apical-base problem, the surgeon should segment the dental models to determine whether good occlusion is achievable. When dental models are cut into segments, each piece is hand-articulated into occlusion and the segments are then reassembled and glued. If the surgeon confirms that this operation can be safely performed on the patient, then he/she is deemed to be ready for surgery.

It is important to note that jaw segmentation should not, routinely, be used to compensate for poor orthodontics. In the absence of apical base problems, poor Class I intercuspation indicates that presurgical orthodontics should continue. In some cases, however, the goal of presurgical orthodontics is not maximal intercuspation. For example, in patients with deep-bite Class II malocclusion, with a deep curve of Spee and a short anterior mandibular height, it may be best not to level the curve of Spee prior to surgery, because this may result in intrusion of the anterior teeth and additional vertical foreshortening of the anterior mandible. A better approach may be to perform surgery before the curve of Spee is leveled. At surgery, the occlusion is set to a normal incisal overbite, with occlusal contacts limited to the incisors and second molars. Postoperatively, an orthodontist levels the mandibular occlusal plane by erupting the premolars, limiting intrusion of the lower incisors.

Once the decision has been made to proceed with surgery, surgical planning begins. A surgeon devises an orthognathic operation by simulating the surgical procedures and visualizing their outcomes. This process is iterated until the desired results are visualized. The approach is called the Visualized Treatment Objective (VTO), a term denoting that the plan is developed by visualizing the final outcome (*i.e.*, the treatment objective).

With VTO, the operation is simulated with models that reproduce the craniofacial anatomy. Traditional planning methods have utilized two-dimensional line drawings of plain cephalograms and stone dental models mounted on a dental articulator; such methods have significant limitations[6, 7, 10, 30-32] and, fortunately, are being phased out. This chapter presents a Computer-Aided Surgical Simulation (CASS) method,[10, 33] which has three phases: modeling, planning, and preparing for plan execution.

MODELING

In the modeling phase, one creates a 3D virtual model of the craniofacial complex. This model should:

- Have a mandible in centric relationship;
- Accurately render the skeleton, the teeth, and the facial soft-tissue; and
- Have a correct frame of reference.

3D virtual models used for CASS should have a mandible in centric relationship. Centric relationship (CR) is the position in which the condyles are centered within the glenoid fossae. It is an important reference position in orthognathic surgery, as it is the only tooth-independent mandibular position that is reproducible.[10, 34, 35] Moreover, in this position, the condyles can rotate for about 20 degrees around an axis that passes near the center of both condyles.[36, 37] Rotation of the mandible around this hinge axis is called *autorotation*.

Having a virtual model in CR is necessary in single jaw maxillary surgery and bimaxillary surgery, if the maxilla is cut first. In these operations, the mandible dictates the location of the maxilla, thus, discrepancy in mandibular position between the virtual model and the patient results in postoperative outcomes that are different from the initial plan. At surgery, the mandible will always be placed in CR; the virtual model should have the same position. Occasionally, before surgery, it is impossible to place the patient in CR (*e.g.*, patients with severe micrognathia). With such patients, the surgeon should consider performing mandibular surgery first, as this obviates the need for accurate CR recording.[34, 38]

Another important feature of 3D virtual models is that they should render the skeleton, the teeth, and the soft-tissue well. Computerized tomography (CT) scans can be used to create 3D models of the craniofacial skeleton, teeth, and soft-tissue. Yet, with these models, the teeth are not sufficiently accurate for the purposes of surgical planning.[30, 39-41] The CASS protocol solves this problem by replacing the inaccurate teeth of the CT with accurate digital dental models.[39] Dental impressions or stone dental models are scanned via optical scanner, a micro-CT, or a cone beam CT to create these models. A model created by merging a CT with digital dental models is called a *composite model*.[33, 39]

The process of aligning digital dental models with the CT scan is called *registration*. It is done by aligning corresponding features that are present in both images. Different algorithms have been developed for this purpose. In these algorithms, the corresponding features can be points (*i.e.*, landmarks),[39, 42] surfaces,[43] or volumes.[44] They can be part of the structures being imaged or they can be fiducial markers—easy to identify parts that are placed in, on, or around the objects before image capture.[45]

Gateno, Xia, *et al.* have developed and validated a fiducial registration system for making composite models.[39] In addition to enabling accurate registration, the system ensures that the mandible is in CR during scanning, which is a key feature.[10, 34] Presented Figure 20, this system uses a two-part device consisting of a bite-jig and a fiducial-facebow.

The bite-jig has a dual purpose: it anchors the facebow to the patient and keeps the mandible in CR during image acquisition. It consists of a customizable stock frame with an anterior male coupler. To customize the jig, a clinician first adds self-cured rigid bite registration material to the frame and subsequently places the jig between the teeth until the material is cured. During bite registration, the clinician seats the mandible into CR.

The plastic facebow attaches to the bite-jig through a female coupler. The facebow has a set of fiducial markers that is used for registration. Before CT scanning, the device—consisting of a bite-jig and a facebow—is assembled and affixed to the patient. A CT scan is then taken while the patient is biting on the device. The resultant images portray the facial anatomy, as well as the fiducial markers.

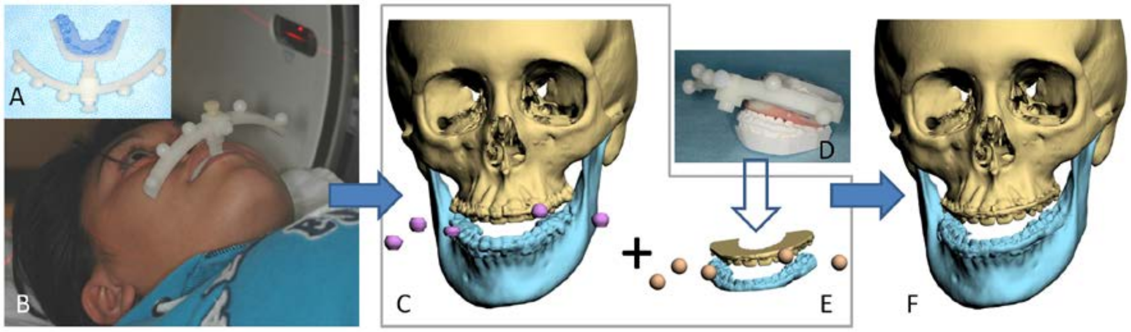


Figure 20. Creation of a composite skull model. **A)** A custom bite-jig is attached to the facebow with fiducial markers (spheres). **B)** The patient bites on the bit-jig during the image acquisition. The mandible is in centric relationship. **C)** Four separate but correlated computer models are reconstructed: a midface model, a mandibular model, a fiducial marker model, and a soft tissue model (not shown). **D)** The bite-jig and facebow is placed between the upper and lower stone dental models during the scanning process. **E)** Three separate but correlated digital dental models are also reconstructed: a maxillary dental model, a mandibular dental model, and a fiducial model. **F)** By aligning the fiducial markers, the digital dental models are incorporated into the 3D CT skull model. The computerized composite skull model is thus created. It simultaneously displays an accurate rendition of both the bony structures and the teeth.

Subsequently, the same device is placed between stone dental models (upper and lower); the models are then scanned. This creates a set of digital dental models surrounded by fiducial markers. In the last step, the digital dental models are registered to the CT, creating a composite model.

As referenced above, a 3D virtual model of the craniofacial skeleton should accurately render the facial soft-tissues. Moreover, it should depict a relaxed position. This is accomplished by asking the patient not to animate his/her face during image capture; also note that deformations produced by posture or external sources should be avoided. Examples of deformities that produce postures resulting in soft-tissue distortion include curling of the lower lip by the upper incisor in Class II deep-bite malocclusions, pouting of the lips from overclosure in vertical maxillary deficiency, downward concavity of the upper vermillion in vertical maxillary excess, and severe anterior open bite. The first two deformations can be avoided by opening the bite, but the latter is unavoidable. As mentioned previously, external sources (*e.g.*, chin-rests, forehead holders, bite-jigs and dental trays, etc.) can also deform the soft-tissues.

Virtual models used for planning must have an accurate *anatomic frame of reference*, as this frame constitutes the basis of most decisions during planning. An incorrectly defined frame of reference can result in postoperative deformity. One can erect a frame of reference for a 3D model by using one of two approaches: anatomical landmarks or the NHP.

The first method uses anatomic landmarks to create a Cartesian frame. At first glance, the task seems trivial. The planner constructs the median plane using any three midline-landmarks. He then makes the axial plane Frankfort horizontal plane, and constructs Frankfurt using 3 of the 4 points that define it (right orbital, left orbital, right porion, and left porion). Finally, he builds the coronal plane, making it pass through both porions, keeping it perpendicular to the other two planes.

Notwithstanding, this simple method only works when the face is perfectly symmetrical. In facial asymmetry, various combinations of three midline landmarks produce different median planes. For the same reason, various combinations of Frankfort points result in different axial planes. Moreover, in facial asymmetry, the Frankfort horizontal is usually not perpendicular to the median plane—a fundamental requirement of the Cartesian system. Finally, a coronal plane cannot be constructed if the two other planes (median and axial) are not perpendicular. Thus, as all faces have some degree of asymmetry, using landmarks to build a frame of reference is highly complex.

The *orthogonal best-fit method* is an approach that takes into consideration the universal asymmetry of the face and the requirement of perpendicularity among the planes. A computer algorithm constructs three orthogonal planes, minimizing the distance between those planes and key facial landmarks. The median plane is the best-fit plane for all midline landmarks, the axial plane is the best-fit plane for the Frankfort landmarks, and the coronal plane is the best-fit plane for both porions. However, as explained below, this method is also flawed.

One example that illustrates why the *orthogonal best-fit method* is unsatisfactory is depicted in Figure 21-A, which shows the 3D CT scan of a hypothetical subject with perfect facial symmetry. In the ensuing year, the patient develops right condylar hyperplasia, resulting in left chin deviation. The rest of her face, including the maxilla, remains unchanged (Figure 21-B). After developing the asymmetry, she seeks treatment. A surgeon sees her and conducts a 3D-CT. He calculates the median plane of the head using the orthogonal best-fit method (depicted as a blue line in Figure 21-C). This method would identify the median plane as the plane that best fits all midline landmarks, but because some midline landmarks are deviated (*i.e.*, the mandible), the median plane will be skewed. Making assessments based on this skewed plane, the surgeon would incorrectly conclude that the maxilla is deviated to the right and the chin is deviated to the left—when, in reality, the maxilla is normal and only the chin is off.

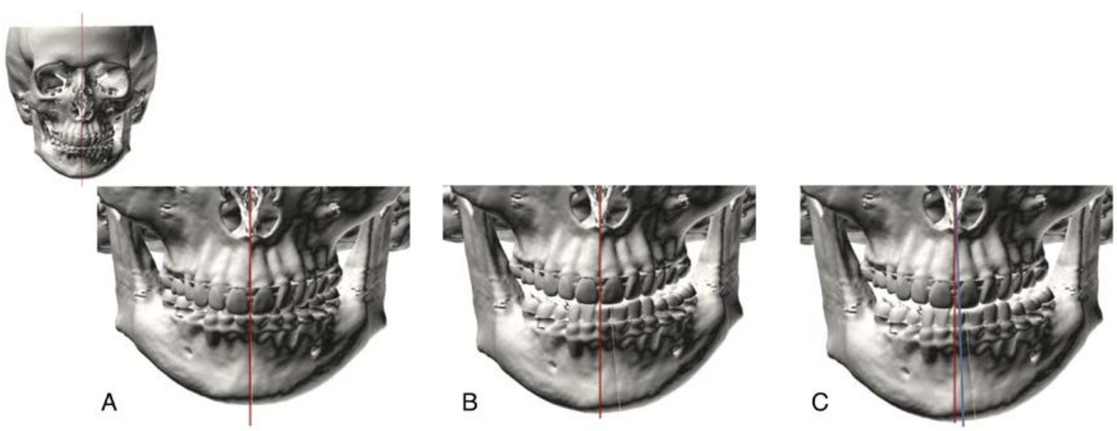


Figure 21. Example that illustrates why using a best-fit method to create a facial frame of reference is inaccurate. **A)** Hypothetical patient with perfect facial symmetry (red line is the median plane). **B)** Simulated unilateral (right condylar hyperplasia). The chin and lower dental midlines are deviated to the left. **C)** Best-fit method erroneously calculates the median plane (blue line).

Why is this the case? Some of the landmarks used by the algorithm are affected by asymmetry. In this instance, the shifted mandibular landmarks skewed the median plane. Thus, one should conclude that facial asymmetries render the landmark method invalid. Moreover, this simple theoretical example caused the authors to reconsider the essence of the anatomical frame of reference, particularly when it involves asymmetry. After some reflection, it is now understood that the anatomical frame of reference a clinician requires is the one a patient would have if he or she did not have an asymmetry: the *primal frame of reference*.

In the hypothetical case presented above, the primal frame of reference can be easily calculated by excluding the skewed mandibular landmarks. Viewed from this perspective, our previous case is simple, as the remainder of the facial skeleton is symmetric. However, when all facial and cranial structures are grossly asymmetric, how does one calculate the frame of reference? A second method that can be used to create an anatomical frame of reference for the entire head—*the natural head posture*—can solve this problem.

The principle behind using the natural head posture (NHP) is that the primal frame of reference of the head can be derived from this posture. When humans stand erect, looking straight forward, the cardinal directions of their faces are orthogonal to gravity. The axial plane is perpendicular to gravitational pull and the median and coronal planes are aligned with it. Thus, when the head is in the NHP, constructing a frame of reference for the face is simple. The axial plane is the horizontal plane that passes through both porions. The median plane is the vertical plane that best divides the face into right and left halves. The coronal plane is the vertical plane that is perpendicular to the other planes and aligned with the coronal suture.

Since the NHP is unaltered by developing jaw asymmetries, the frames of reference calculated by this method are unaffected by such deformities. Unfortunately, NHP is inconsistent for two reasons. First, some patients have difficulty aligning their heads in the NHP. This is especially true of children, patients with neuromuscular problems, patients with torticollis, and patients with eye muscle imbalances. Second, even within the same patient, there are temporal variations in the NHP. When one records the NHP on the same patient, at various intervals, one obtains different measurements. Most of the time, the measurements are in close proximity, varying within two degrees—yet, even these small variations are problematic. Figure 22 presents the example of a symmetric patient who rolled his head (around nasion) by two degrees during NHP recording. This small error caused the upper incisal midpoint and pogonion to appear right-deviated—the upper incisal midpoint by 1.6 mm, and pogonion by 2.6mm—when they were not. These are significant errors.

There are two ways of orienting a CT scan to the NHP. One is to scan the head while in the NHP; the other is to scan the head in any orientation and then reorient the resultant image to the NHP. CT scanners are aligned with the world, an alignment that takes into consideration the orientation of the patient's body during scanning (*i.e.*, supine or erect). If we place a patient in the NHP during CT acquisition—or its equivalent for a supine patient—the resultant image will automatically be in the NHP. Although this method seems simple, in practice it is difficult to implement. In medical CT scanners, it is hard to set the head in the NHP when the patient is supine. In a cone-beam CT scanner, where patients sit, chin-rests and head-holders commonly interfere with the NHP. Therefore, reorienting images into the NHP after CT acquisition is ultimately more practical.

Three methods can be used to reorient a randomly oriented 3D CT to the NHP: 1) standardized photographs,[10] 2) laser levels,[46, 47] and 3) orientation sensors.[10-12]

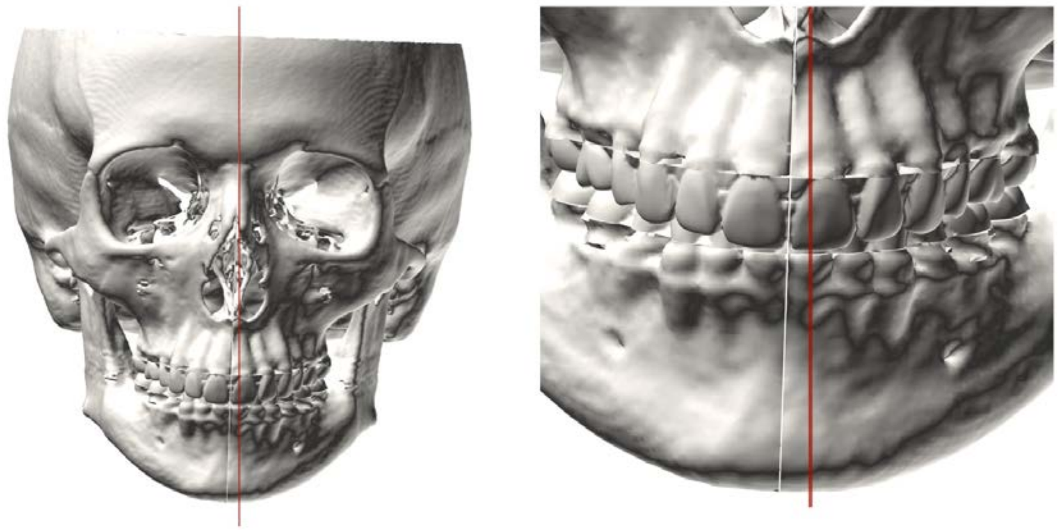


Figure 22. Consequence of NHP recording error. This symmetric patient rotated his head 2 degrees clockwise during NHP recording. It caused the upper and lower dental midlines to look deviated when they were not.

In the first method, standardized frontal and lateral facial photographs taken with the patient in the NHP serve as visual guides to manually reorient the 3D CT in the computer. Although this method is subjective, it is valuable for checking the outcome of advanced methods.

In the second method, a patient is placed in the NHP. Then, the perpendicular lights of a laser-level are projected onto the face of the patient and the level is moved until the laser's vertical line is on the patient's median plane and the horizontal line crosses the external auditory canals. Next, a skin marker (*i.e.*, a pen) is used to delineate six points on the skin of the face, establishing the orientation of the reference lines directly onto the patient. Following this, radiopaque markers are tapped on the skin markings and the patient is CT scanned. After scanning, the markings are used to build an anatomical frame of reference. Unfortunately, this method has not been formally validated. A theoretical disadvantage is that it relies on skin landmarks that can be easily displaced.

The third method of reorienting a CT to the NHP uses an orientation sensor to record the NHP before CT scanning (Figure 23). The sensor is attached to the same bite-jig used for registration. Next, the patient, with the bite-jig between his teeth and the sensor in front of it, stands erect with his head in the NHP. In this posture, the pitch, roll, and yaw of the sensor are recorded. Because the sensor is orthogonal to the bite-jig frame, the orientations of the sensor and the frame are always equal. By establishing the orientation of the sensor while the patient is in the NHP, the orientation of the frame of the bite-jig for the same posture is also established. In the next step, the sensor is detached from the bite-jig and a fiducial facebow is attached orthogonally to the bite-jig, giving the bite-jig frame and the facebow the same orientation. Subsequently, the patient is CT scanned while holding the bite-jig and facebow. Thereafter, the CT, including the imaged facebow, is segmented and rendered as a 3D model.

Finally, the 3D model is rotated until its facebow attains the measured NHP orientation, placing the whole 3D model in the NHP. The advantage of this method is that it has been validated *in vitro* and clinically.

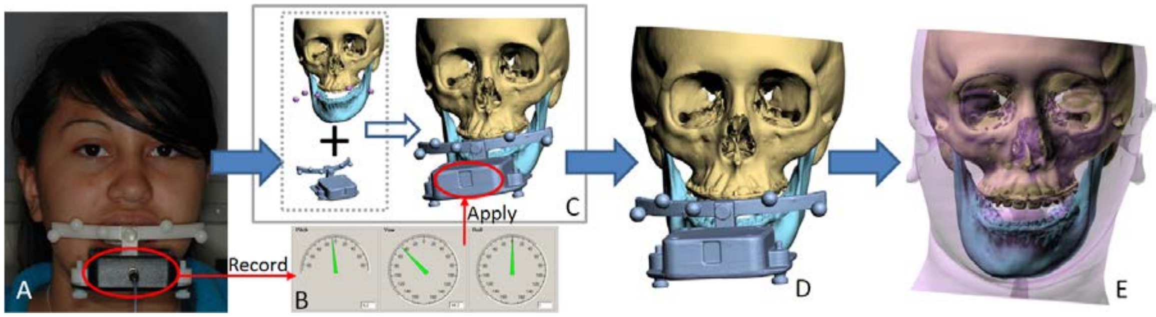


Figure 23. Recording the NHP with a digital orientation sensor. **A)** A digital orientation sensor is attached to the bite-jig and facebow. **B)** The pitch, roll and yaw of the sensor are recorded. **C)** In the computer, a digital replica [computer-aided designing (CAD) model] of the orientation sensor is registered to the composite skull model via the fiducial markers, and the two objects are attached to each other. **D)** The recorded pitch, roll and yaw are applied to the facebow frame, reorienting the composite skull model to the NHP. **E)** After the composite skull is oriented to the NHP, the CAD model of the orientation sensor is marked hidden.

In conclusion, both methods currently used to erect frames of reference for the head—the anatomic landmark method and the NHP method—have significant limitations. With this in mind, the authors' laboratory is now developing new methods to calculate the primal frame of reference for the face, with the goal of eliminating errors that result from existing methods.

PLANNING

In CASS, surgery is planned using a VTO approach, meaning that surgery is simulated until the desired final outcome is attained. Surgical simulation is done on three-dimensional composite models, using specialized software. These programs can perform three basic functions: cutting and moving bones, articulating teeth, and morphing soft-tissue.[48]

CUTTING AND MOVING BONES

Bone cutting is a computer operation that simulates an osteotomy. The cutting tool can be set as a simple plane or a three-dimensional array of adjacent planes. Both options are customizable for position, orientation, size, and thickness. To make a cut, an operator first sets the cutting tool into the planned osteotomy and then activates the cutting command. This operation separates an object into two new objects that can be distinguished through recoloring or renaming.

Moving bones involves two different types of transformations: translation and rotation. Translation is movement without rotation (*i.e.*, sliding); rotation is turning around a point. During planning, both types of transformations are required. Translation can be made in the direction of the axes of the coordinate systems; whereas, rotation can be made around any pivot point. With the software, the user can select the center of rotation.

Before translating or rotating objects in the computer, sometimes it is convenient to form groups of objects. In computer terms, this is known as object linkage.[49, 50] Linkage allows a transformation to be applied to the entire group, as opposed to a single object. One example occurs in single jaw maxillary surgery. In these circumstances, the maxilla is first moved toward the mandible, placing it into final occlusion—usually maximum intercuspation. Next, the maxilla is linked to the mandible, so both can be rotated around the mandibular hinge axis without disrupting the final occlusion. Then the maxilla and mandible are rotated as a group until the maxillary central incisors are placed in an ideal vertical position.

Another example occurs in bimaxillary surgery, wherein the distal mandible is first moved toward the maxilla, placing it into final occlusion; subsequently the mandible is linked to the maxilla, so the maxilla can be moved without disrupting the occlusion. Maintaining the final occlusal relationship throughout all maxillary movements simplifies planning, as the distal mandible will automatically be in final position once the maxillary movements are complete.

Dental Articulation

In traditional planning, final occlusion is established by hand-articulating stone dental models. This maneuver is quick and reliable; early contacts are easily noted, facilitating occlusal adjustments. Yet establishing final occlusion digitally is challenging. Upper and lower digital dental models are images that can overlap. Moreover, in CASS there is no tactile sensation, nor are there real-time collision constraints. For these reasons, placing two dental models into occlusion becomes time consuming. Furthermore, there are uncertainties regarding the best alignment outcome. This is even more difficult when occlusal adjustments and/or dental arch segmentation are required. Although the authors[43, 51-54] and others[55-57] are working to resolve these issues, our clinical routine presently employs physical models as an intermediate step.

In the current CASS routine, final occlusion is first established on stone models. The models are then scanned in final occlusion, creating a *digital-final-occlusion-template* (Figure 24). This template is a computer object depicting upper and lower teeth in final occlusion. It has two parts: top (upper teeth) and bottom (lower teeth). Once the template has been created, it is imported into the CASS software, where it is used to align the jaws of the composite model into final occlusion. The alignment is a simple two-step process. First, the template is aligned to one of the jaws. Then, the other jaw is aligned to the template. As in the template, the upper and lower teeth are in final occlusion; aligning one part of the template to one jaw and then the opposite jaw to the template automatically places the jaws into final occlusion.

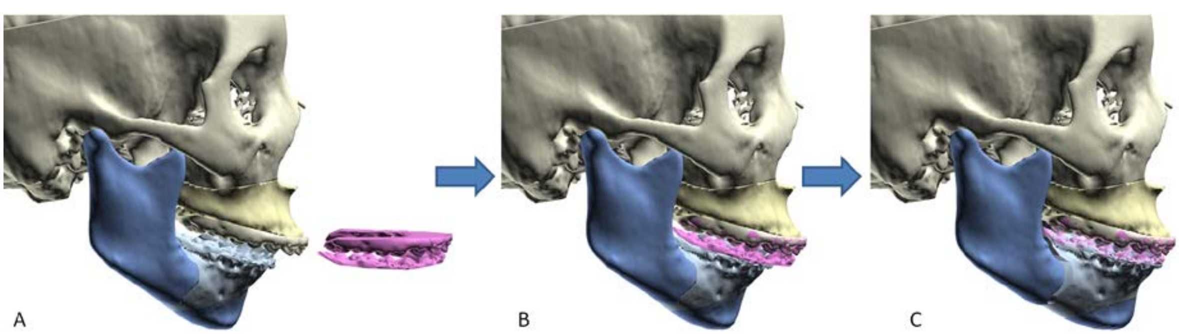


Figure 24. Incorporating the final-occlusal-template and placement of the mandibular distal segment into final occlusion in a single-piece Le Fort I osteotomy. **A)** In this example, virtual osteotomies, including a single-piece Le Fort I osteotomy and bilateral sagittal split osteotomy, are completed. Each bony segment is located in its original location. **B)** The digital final-occlusal-template is generated by scanning the hand-articulated stone models using a high-resolution scanner. **C)** The upper part (maxillary teeth) of the final-occlusal-template is first registered to the maxillary teeth in the composite model. **D)** The mandible is set to the final occlusion by registering the distal mandibular teeth to the lower part (mandibular teeth) of the template.

When the maxilla is the only jaw involved in the surgery, the template is first aligned to the lower teeth and then the upper jaw is aligned to the template. When the mandible is the only jaw involved in the surgery—or when both are—the opposite sequence is undertaken.

When the dental arches need segmentation, the use of a digital template to align teeth into final occlusion is more complicated. This scenario is best illustrated using the following example: a patient who requires a 3-piece LeFort I osteotomy and a mandibular ramus-osteotomy. As before, the occlusion is first established on stone dental models. For this patient, the upper stone dental model is cut into three pieces, and each piece (*i.e.*, segment) is independently moved and articulated into final occlusion. The intact lower arch is used as a guide. The independent movement of each segment changes the size and shape of the upper arch, creating a new intra-arch relationship among the upper jaw segments.

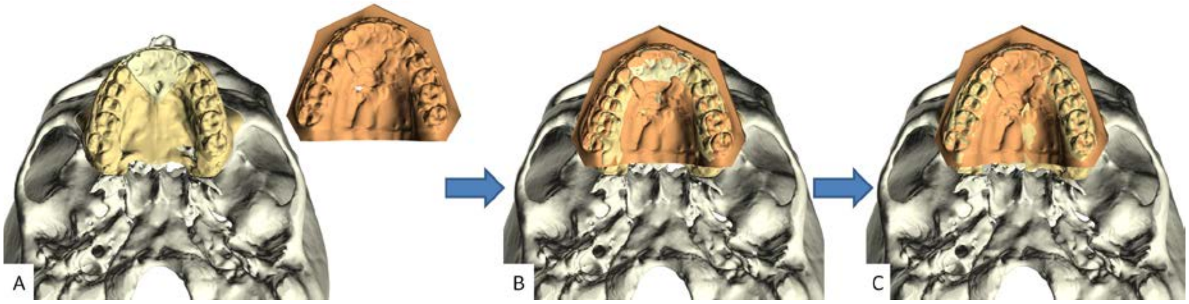


Figure 25. Incorporating the final-occlusal-template in a multiple-piece Le Fort I osteotomy. **A)** In this example, a three-piece Le Fort I osteotomy is completed. All bony segments (yellow) are located in their original positions. **B)** The upper part (maxillary teeth) of the digital final-occlusal-template. The template is also generated by scanning the hand-articulated stone, in which the upper stone model is first cut into three pieces, then hand-articulated to the final occlusion without using an articulator. Note that the posterior Le Fort I segments in the composite skull model are medially positioned at this stage. **C)** The upper part of the final-occlusal-template is registered to the maxillary teeth at the central dental midline, best fitting the posterior parts of the teeth. D) All Le Fort I segments are then perfectly registered to the corresponding segment in the final-occlusal-template, resulting in a new intra-arch relationship among the Le Fort I segments.

In the next step, one scans the stone dental models, creating a digital-final-occlusion template that not only captures final occlusion, but also depicts the new intra-arch relationship among the upper jaw segments. After importing a digital occlusal-template into the CASS software, the template must be aligned to the upper teeth of the composite model (Figure 25). However, in the case of arch segmentation, the geometries are dissimilar; that is, the template shows the *new* upper arch alignment, whereas the composite model shows the *original* condition. In this circumstance, the template is aligned to the upper jaw in two steps. First, the upper teeth of the template are *best aligned* to the teeth of the upper jaw. Then, the upper jaw of the composite model is sectioned and each LeFort segment is aligned to the template—at its corresponding place. A similar approach is used when the lower arch is segmented.

Soft-Tissue Morphing

Current software packages are capable of simulating soft-tissue changes that occur with the movement of osseous or dento-osseous segments, and they employ different strategies to achieve that goal. The simulation methods must be accurate and fast. Yet attaining both is difficult because these attributes are inversely related; the more accurate the model, the longer it takes to prepare and run. The facial soft-tissue envelope is a heterogeneous structure composed of different types of tissue: skin, fat, connective tissue, muscle, and mucosa, each one with different mechanical properties. [58] Moreover, the properties are complex, as they are non-linear and anisotropic.[58, 59]

Several models have been used to simulate soft-tissue deformations. They include: *empirical-based models,*[60-63] *mass spring models,*[64-66] *finite element models,*[61, 65, 67-72] and *mass tensor models.*[73, 74]

Empirical-based models calculate soft-tissue deformation by using bone-to-soft-tissue change ratios derived from empirical knowledge[63] or statistical calculations.[60] This method is fast,[60, 63] but inaccurate,[61, 73] as it does not consider actual biomechanical tissue properties.[60, 69, 73]

Mass spring models were initially developed for animation by the gaming industry, where rendering speed is more important than accuracy. In a *mass spring model*, the facial soft-tissue volume is represented as a 3D array of vertices (masses) attached by springs. Though quick, this method lacks biomechanical relevance and clinical accuracy.[60, 69, 73]

Finite element models divide the entire soft-tissue volume into a large number of geometrically discrete volumes and assign material properties to them.[73] These models can vary from simple to complex. The simplest models assign a single homogeneous material property to the entire soft-tissue envelope. The complex models fashion the envelope as a composite with different material properties. *Finite element models* are more accurate than *mass spring models*, as they have true biomechanical relevance. However, preparation and computation time for *finite element models* are significant (usually 20 hours to 3 days, depending on the complexity of the model). The authors' laboratory has solved this problem by using an eFace-template method to efficiently generate a patient-specific, anatomically-detailed, facial soft tissue finite element model within minutes.[75]

Finally, *mass tensor models*—which can be considered a hybrid of *mass spring models* and *linear finite element models*—employ a homogenous tissue property. They are reported to have fast computation times and acceptable accuracy.[73]

Planning Algorithms

Orthognathic surgery is performed to treat deformities that can affect one or both jaws. Planning a single-jaw surgery is simpler than planning a double-jaw operation. The following sections present planning algorithms for single- and double-jaw surgery, beginning with the simplest scenario and ending with the most complex.

Single-jaw Maxillary Surgery

In CASS, the simplest surgery to plan is single-jaw maxillary surgery, an operation that is performed when the maxilla is deformed and the mandible is normal (Figure 26). In this scenario, the planner will make three decisions: final occlusion, vertical maxillary position (*i.e.*, the position of the upper *dental midpoint)*, and an assessment to determine the need for complementary genioplasty.

The surgeon begins the planning process by simulating a LeFort I osteotomy. When the dental arch needs segmentation, the maxilla is cut into two or more pieces. Next, the maxilla is placed into final occlusion by articulating the entire jaw, or its segments, on the mandible. Currently, this is accomplished with the help of a *digital-occlusal-template.* When the maxilla is cut into pieces, the pieces are rejoined after they have been moved. This allows the maxilla to be moved in the future as a single piece.

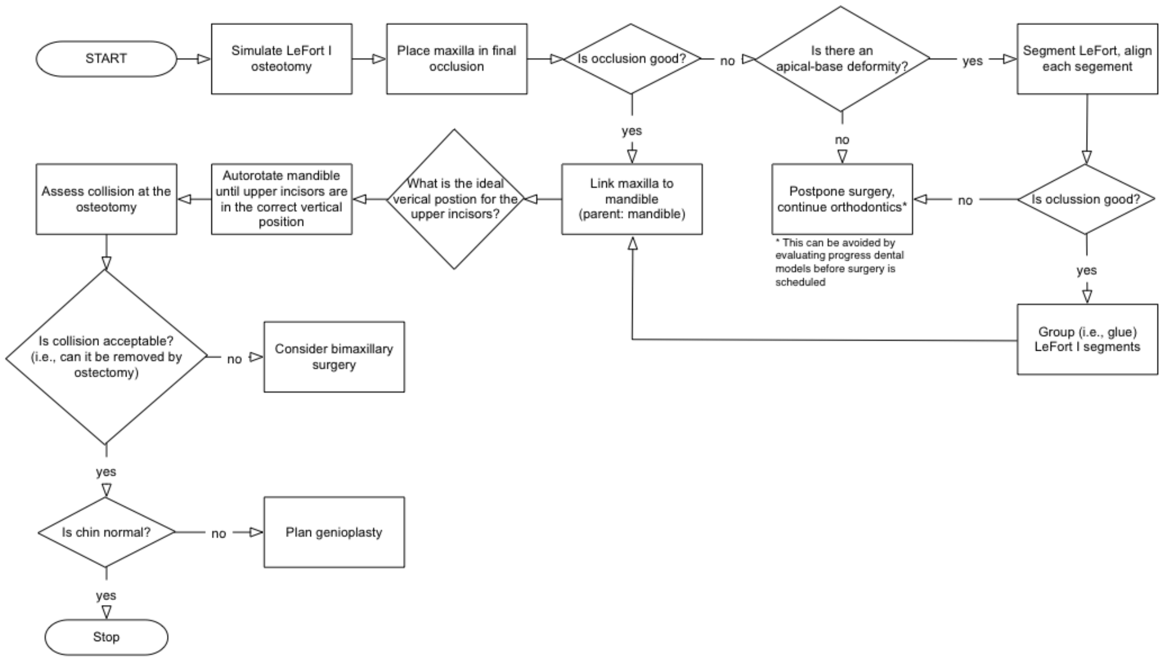


Figure 26. Single-jaw maxillary surgery flowchart (with or without genioplasty).

Once final occlusion has been determined, the planner links the maxilla to the mandible. Linkage facilitates the next step, *autorotation*. In autorotation, the mandible is rotated around the condylar axis. Linking the maxilla to the mandible maintains final occlusion during the rotation.

Having already determined the ideal vertical position for the upper incisal midpoint (see the evaluation section), the planner autorotates the mandible until the upper incisal midpoint reaches the desired vertical position. Next, the osteotomy site is assessed. Depending on the maxillary movement, the site may have gaps, butt joints, and regions of overlap.

During surgery, regions of overlap correspond to regions of bony collision. Thus, one should pay particular attention to these areas during the planning process. Note that ostectomies of regions of overlap can prevent collision. Notwithstanding, large areas of overlap in or around the descending palatine artery, pterygoid plates, and the tuberosities are best avoided, as resecting large volumes of bone in these areas is difficult. If the overlap is unacceptable, the planner should consider bimaxillary surgery.

In the final step of planning a single-jaw maxillary surgery, the surgeon reassesses the chin. Reevaluation is required because chin projection changes with autorotation. If the chin is normal, the plan is finished.

If it is abnormal, the planner should simulate and plan a genioplasty.

SINGLE-JAW MANDIBULAR SURGERY

The next most complex plan is single-jaw mandibular surgery, an operation performed when the mandible is deformed and the maxilla is normal (Figure 27). Assuming it involves osteotomies of the mandibular rami (sagittal, vertical, or inverted L osteotomies), one must make four decisions: final occlusion, right proximal segment alignment, left proximal segment alignment, and final symmetry.

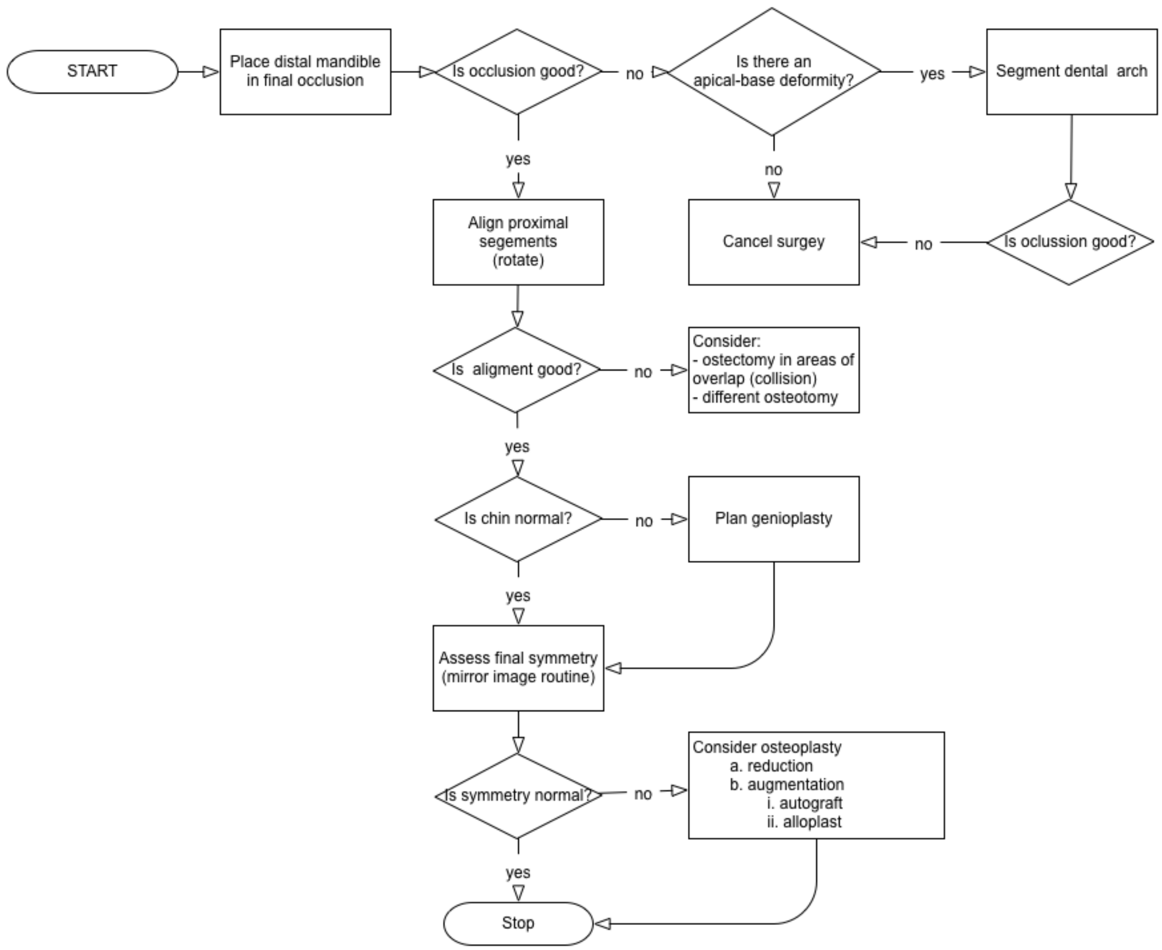


Figure 27. Single-jaw mandibular surgery flowchart (with or without genioplasty).

In the first step of planning, one simulates the osteotomies, usually in both rami. Sometimes, however, a body osteotomy is also necessary (*e.g.*, segmental dentoalveolar osteotomy, total dentoalveolar osteotomy, or a symphyseal osteotomy). Bilateral ramus osteotomies divide the mandible into three pieces: a distal segment containing the dentition and two proximal segments (right and left), including the condyles.

In the next step, the planner places the dentate segment(s) into final occlusion. Then, the proximal segments are aligned. Each proximal segment is rotated around the center of its condyle until the segment is well aligned with the distal mandible. Ideally, there should be no overlap between the segments, as overlap corresponds to areas of bony collision that can produce proximal segment misalignment at surgery. When overlap is noted, the surgeon should consider ostectomy of the area of overlap or a different osteotomy. Small regions of overlap are amenable to ostectomy; large regions require an alternative operation.

In the following step, the planner reexamines the chin. This is necessary because movement of the mandibular distal segment alters chin position. If the chin is normal, the planner proceeds to the final step; if abnormal, the planner should simulate a genioplasty, moving the chin segment until he/she is satisfied with the outcome.

In the last step, the planner assesses *final symmetry*. When the maxilla is normal and the mandible is abnormal but symmetric, placing the distal mandible in final occlusion maintains symmetry. However, when patients have intrinsic mandibular asymmetry, placing the distal mandible into final occlusion does not correct the asymmetry. Since mild to moderate degrees of intrinsic asymmetry may be imperceptible to the eye, it is important to complete a final symmetry assessment on all patients. This is performed using a *mirror-image routine* (Figure 28), in which the composite model is cut in half across the median plane. One side is then copied and reflected (flipped) across the median plane, superimposing it over the contralateral half. Subsequently, right-left differences are calculated using a Boolean subtraction—a mathematical method that reveals differences between objects. If the symmetry is good, the plan is complete; if there is residual asymmetry, the surgeon should consider an osteoplasty (reduction or augmentation). The latter can be achieved with bone grafts or alloplasts.

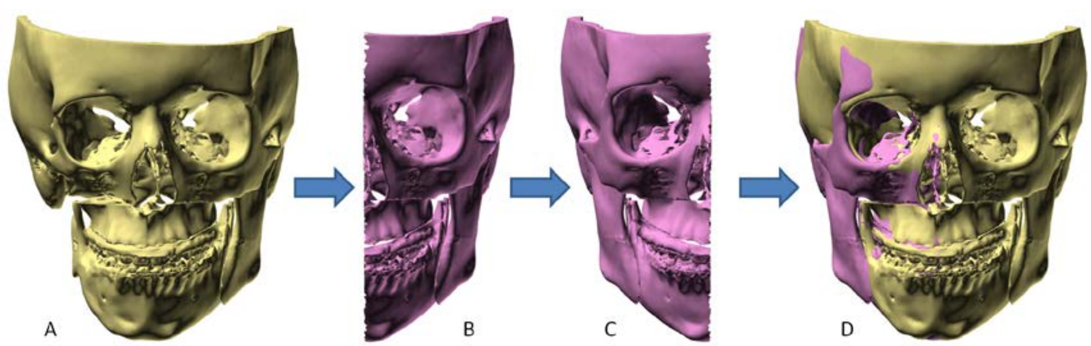


Figure 28. Mirror-image routine. **A)** The planned outcome after all bony segments are moved to their desired positions. **B)** One side of the face is first copied. **C)** The copy is flipped horizontally. **D)** The flipped copy is superimposed on the contralateral side; finally, side-to-side differences are calculated.

DOUBLE-JAW SURGERY

A double-jaw surgery is necessary when both jaws are deformed or when the discrepancy between the jaws is so large that both jaws must be moved, even if one of them is normal. Planning a double-jaw operation is a complex, multi-step process. Planning without having a strategy costs time, produces errors, and results in unsatisfactory outcomes. The authors have developed a planning algorithm to guide surgeons through this process (Figure 29).[25, 48]

Planning begins by simulating osteotomies in the maxilla and mandible. In the maxilla, one performs a LeFort osteotomy. In the mandible, one usually conducts bilateral ramus-osteotomies, but occasionally, body osteotomies are required as well. If dental arch segmentation is unnecessary, one proceeds to the next step: articulating the maxilla atop the mandible into final occlusion. If arch segmentation is needed, the planner first cuts the jaws into pieces and then articulates each piece into final occlusion. Aligning the jaws into final occlusion is achieved with the aid of a digital-final-occlusion-template.

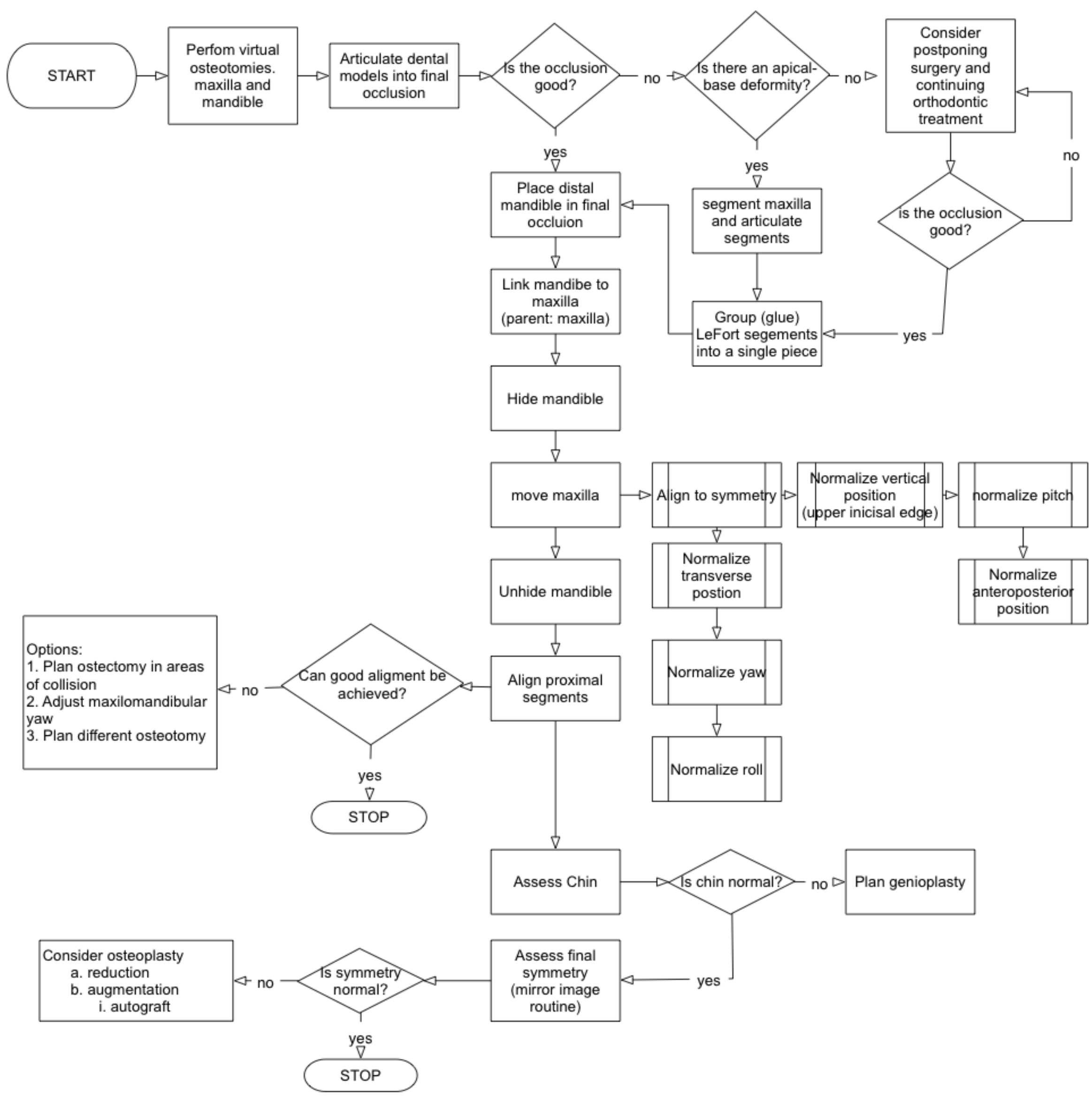


Figure 29. Double-jaw surgery flowchart (with or without genioplasty).

When the jaws are segmented, one must regroup the segments after they have been moved. Regrouping is the digital equivalent of gluing segments during physical model surgery. It allows reestablishment of the maxilla or distal mandible as a single piece, which facilitates future movements.

The next step is linking the distal mandible to the maxilla. This ensures that the distal mandible moves simultaneously with the maxilla. If the distal mandible is unlinked, the maxilla will move without the mandible, resulting in altered occlusion. Because the jaws are already in final occlusion, it is important to for them to move together.

The mandible is then hidden and the maxilla is moved into ideal alignment. A series of transformations (translations and rotations) is required to reach this alignment; transformations are best done on or around a single point, following a specific sequence. Empirically, the authors have determined that, in order to avoid iterations, the optimal point at which all transformations should be performed is the *incisal midpoint*. To this end, the authors have established the following planning sequence:

- Symmetric alignment
    - Normalization of transverse position
    - Normalization of yaw
    - Normalization of roll
- Normalization of vertical position
- Normalization of pitch
- Normalization of anteroposterior position

In the first step, the maxilla is symmetrically aligned to the median plane. This involves three transformations: transverse translation, yaw rotation, and roll rotation. Transverse translation places the maxillary *incisal midpoint* on the median plane. Yaw rotation pivots the maxilla around the incisal midpoint, making the posterior teeth as equidistant as possible to the median and coronal planes. Finally, roll rotation pivots the maxilla around the incisal midpoint until right and left teeth are vertically aligned.

In the second step, the vertical position of the maxilla is normalized. The planner translates the maxilla up or down, placing its incisal midpoint in an ideal position—in relation to the upper lip stomion.

In the third step, one normalizes the maxillary pitch. The planner pivots the maxilla around the incisal midpoint until its pitch is optimized. Maxillary pitch rotation affects the following:

- Inclination of the maxillary central incisors
- Inclination of the maxillary occlusal plane
- Airway size
- Projection of the anterior nasal spine (ANS)
- Chin projection

When deciding the ideal maxillary pitch for a given patient, one should take into account all five of these factors. The first three relate to function, the last two to aesthetics. Frequently, the planner must make compromises among these variables, in accordance with individual case parameters and priorities.

The inclinations of the maxillary central incisors and the occlusal plane are important for disocclusion—the separation of upper and lower teeth during eccentric movement of the mandible. The average inclination of the maxillary central incisors to the horizontal plane is 117.0˚± 6.9˚ for a male and 110.5˚± 9.1˚ for a female.[76] The average occlusal plane inclination to the horizontal plane is 9.3˚± 3.8.[77] These values are useful when determining the maxillary pitch.

Regarding the airway, decreasing maxillary pitch increases mandibular projection. When the mandible moves forward the tongue moves with it, thereby enlarging the retroglossal airway space; the opposite occurs when maxillary pitch is increased.

Concerning projection of the anterior nasal spine (ANS) and chin, increasing maxillary pitch (by rotating the maxilla around the incisal midpoint) increases projection of the ANS, thereby decreasing projection of the chin. Increasing the ANS projection rotates the nasal tip upward, widening the nasolabial angle; decreasing maxillary pitch has the opposite effect.

The final adjustment required to align the maxilla is focused on the anteroposterior position. The authors leave this adjustment for last because previous transformations can alter one's decision regarding how much to advance the maxilla. For example, decreasing maxillary pitch or changing its yaw can produce collision between the maxillary tuberosities and the pterygoid plates—collisions that can be easily avoided by advancing the upper jaw.

After the maxilla is in ideal alignment, the mandible is rendered. The distal segment of the mandible will automatically be in final alignment because of its previous linkage with the maxilla in final occlusion. Note that each of the transformations previously applied to the maxilla have been transferred to the distal mandible.

In the following step, the proximal segments of the mandible are aligned. Each proximal segment is rotated around the center of its condyle until the segment is well aligned with the distal mandible. Ideally, there should be no overlap between the proximal and distal segments, as overlap corresponds to areas of bony collision. When present, segment overlap can be mitigated by:

- Readjusting the yaw of the maxilla and distal mandible
- Planning a resection (ostectomy) of the areas of overlap
- Planning a different ramus osteotomy

Readjusting the yaw of the maxilla and distal mandible by one or two degrees can obviate proximal segment collision without altering aesthetics. Adjustments larger than two degrees should be avoided as they can produce buccal corridor asymmetry—the right-to-left difference in the amount of posterior teeth displayed when smiling. To prevent displacement of previous corrections, all yaw readjustments must be made around the upper incisal midpoint.

Small areas of bony overlap are amenable to ostectomy, but large areas of collision that remain after maxillary yaw adjustment can only be avoided by selecting a different operation (*e.g.*, an inverted L osteotomy over a sagittal split).

The final two steps: *chin assessment* and the *assessment of final symmetry* are the same as those performed for single-jaw mandibular surgery. Figure 30 shows a clinical example of a patient whose bimaxillary orthognathic surgery was planned with CASS.

Preparing for Plan Execution

Planning has no value if the plan cannot be realized at surgery. The ultimate goal is a surgical outcome that is identical to the planned result. In orthognathic surgery, this is attained when the surgeon

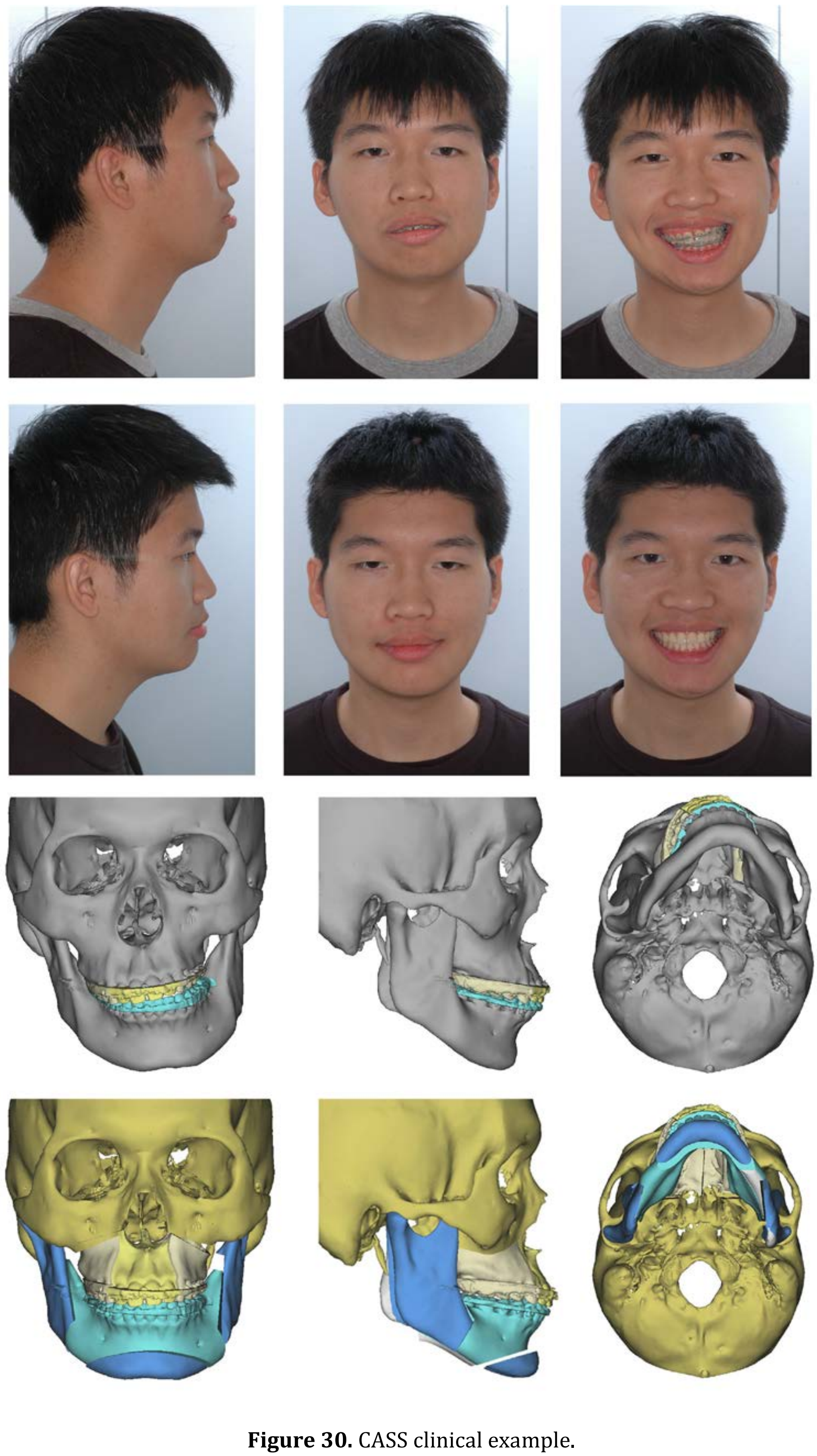


Figure 30. CASS clinical example.

accurately moves the bone segments to their planned location. Various procedures and appliances have been developed for this purpose and require preparation prior to surgery. In this section, we discuss how to prepare for the execution of a surgical plan.

Jaw osteotomies can give rise to two types of movable bone segments: dentate and non-dentate (*i.e.*, with and without teeth). The type and number of segments produced depends on the location of the osteotomies. For example, in a genioplasty, one movable non-dentate segment is created. In a standard LeFort I osteotomy, a single dentate segment is produced. In mandibular rami osteotomies, three segments are created: one distal and two proximal; the distal is dentate; the proximals are not.

During orthognathic surgery, a surgeon must relocate all movable jaw segments (dentate and non-dentate). The new location of the dentate segments is established using *occlusal surgical splints*. These splints are arch-shaped, removable, plastic appliances placed between the occlusal surfaces of the upper and lower teeth to relocate and temporarily stabilize jaw segments.

There are two types of occlusal splints: *intermediate* and *final*. *Intermediate splints* are used exclusively in double-jaw surgery, which is performed in sequence (one jaw, then the other). During surgery, the surgeon first cuts and moves one jaw, places it in its new alignment, and fixates it; the same is then done on the other jaw. Intermediate occlusal splints are devices that relate the dentate segments of one jaw—the first to undergo surgery—to the unmoved dentate segment of the other.

Final splints place dentate segments into *final occlusion*, which is the planned occlusion at the end of surgery. Final splints are needed when the final occlusion is unstable (*e.g.*, prone to slipping) or when interdental osteotomies are used to segment the dental arch (*e.g.*, 3-piece LeFort I, Hofer osteotomy, etc.). They are used in both single- and double-jaw surgery.

In CASS, both types of splints—intermediate and final—are designed in the computer and subsequently fabricated using rapid prototyping techniques.[10, 33, 34, 78, 79] To create an intermediate splint, the computer model shows the first jaw in its final alignment and the second jaw in its original condition. If present, collision (*i.e.*, overlap) between the upper and lower teeth is avoided by rotating the mandible open. Next, a three-dimensional arch-shaped pattern is placed between the upper and lower teeth, and the teeth are subtracted from the pattern. The resultant digital splint is then fabricated via rapid prototyping (Figure 31); a non-toxic sterilizable material is used for this purpose. The final splint is created in a similar fashion, with the exception that the computer model is placed in final occlusion, for the final outcome (Figure 31).

When double-jaw surgery involves segmentation of the dento-alveolus of the first jaw, the use of separate—intermediate and final—splints is time consuming. In such cases, a surgeon performs the following steps:

1. Cuts the first jaw, creating two or more dento-osseous segments
2. Locates and wires each of the dento-osseous segments into the *intermediate splint*
3. Places the splint on the opposite jaw (uncut jaw)
4. Wires upper and lower teeth together, using maxillomandibular wires
5. Fixates the first jaw, using plates and screws
6. Removes the wires and the intermediate splint
7. Cuts the second jaw
8. Wires each of the dento-osseous segments of the first jaw into the *final splint*
9. Places the dentate segment of the second jaw into the final splint
10. Wires upper and lower teeth together, using maxillomandibular wires

11. Fixates the second jaw

In these cases, using a *sandwich occlusal splint* rather than separate intermediate and final splints, simplifies and shortens surgery. A *sandwich occlusal splint* is a two-part splint made by interlocking final and intermediate splints. This splint is fabricated in the following fashion. First, a regular final splint is fabricated with both jaws in their final position (Figure 32A). Next, the second jaw on which surgery will be performed is rendered in its original form (uncut) while the final splint is left on the segmented first jaw. Then, the bite is opened to avoid collisions and the intermediate splint is fashioned between the final splint and the uncut jaw (Figure 32B).

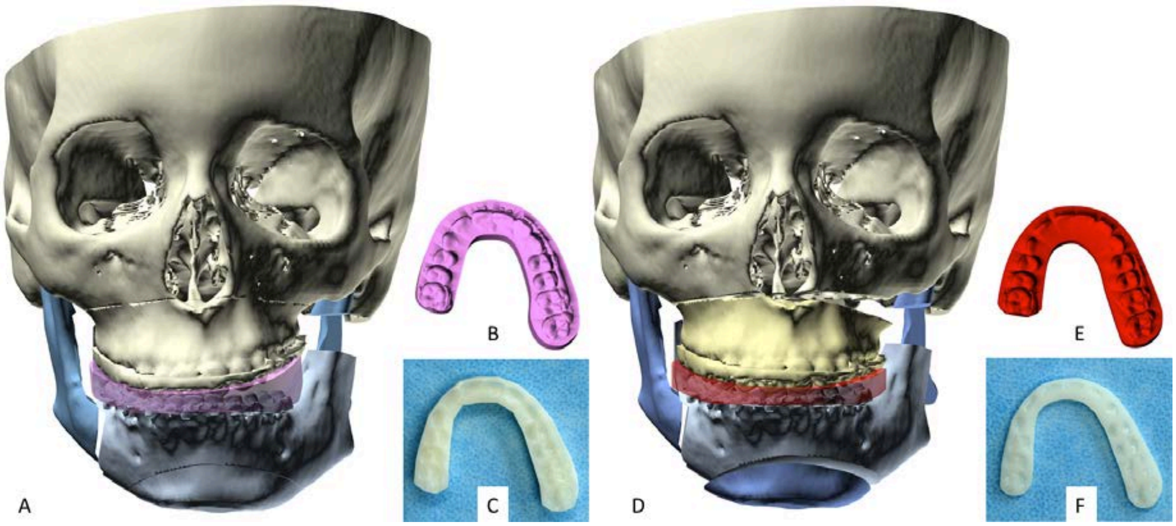


Figure 31. Intermediate occlusal splint (A, B, and C). Final occlusal splint (D, E and F).

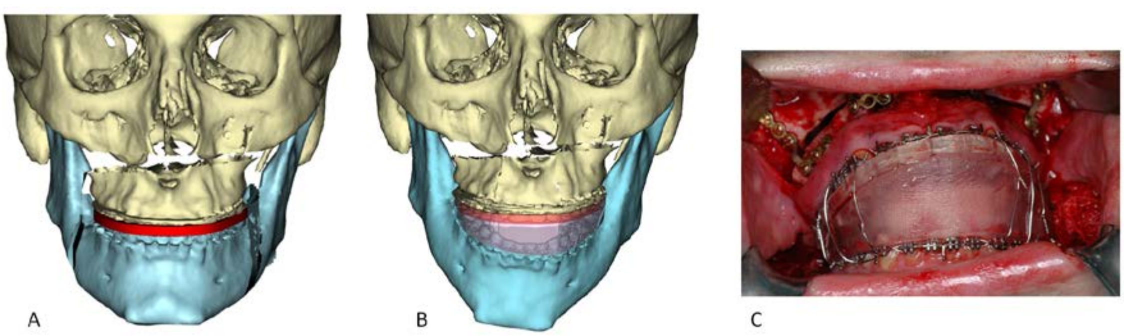


Figure 32. Sandwich splint. **A)** A final splint is first designed. **B)** An intermediate splint is then designed between the final splint and the uncut jaw. **C)** Intraoperative use of a sandwich splint.

When using a sandwich splint, the surgeon:

1. Cuts the first jaw, creating two or more dento-osseous segments
2. Locates and wires each of the dento-osseous segments into the *final splint*
3. Places the intermediate splint between the final splint and the opposite jaw
4. Wires upper and lower teeth together, using maxillomandibular wires
5. Fixates the first jaw, using plates and screws
6. Removes the wires and intermediate splint
7. Cuts the second jaw
8. Places the dentate segment of the second jaw into the final splint
9. Wires upper and lower teeth together, using maxillomandibular wires
10. Fixates the second jaw

A *sandwich splint* eliminates one step: wiring each of the dentoalveolar segments (of the first jaw) into the intermediate splint—a task that is tedious and time consuming. Figure 32C shows the intraoperative use of a sandwich splint. The photo shows the final splint stabilizing three maxillary dentoalveolar segments and the intermediate splint—located between the final splint and the lower jaw—thereby relocating the upper jaw.

Occlusal splints place dentate-osteotomy segments into planned alignment. These devices are all one needs to reposition the dentate segments of the mandible, but they are insufficient for the maxilla. In maxillary surgery, the upper jaw is articulated against the mandible, a movable bone. A cut upper jaw moves even when wired to the mandible. Thus, for maxillary surgery, one requires additional methods to set the maxilla into final alignment. In addition to using splints, surgeons restrict mandibular movements to rotation by placing the mandible in centric relationship; vertical maxillary position is controlled by using intraoperative measurements.

At surgery, before cutting the upper jaw, a surgeon inserts a K-wire into the nasal bones. From this external reference, the baseline vertical maxillary position is established by measuring the distance between the K-wire and the *upper incisal midpoint*. Next, the target vertical position is calculated by adding or subtracting the planned vertical change to or from the baseline measurement. After mobilizing the maxilla and wiring it to the mandible, the mandible is placed into centric relationship and the maxillomandibular complex is rotated up or down until the upper incisal midpoint reaches the target distance. In this position, the maxilla is fixated.

In orthognathic surgery, non-dentate segments arise in the mandible after osteotomies of the rami or chin. The non-dentate proximal segments of mandibular ramus osteotomies (sagittal split, vertical, or inverted L) reach their final alignment when the relationship between the proximal and distal segments visualized in CASS is reproduced at surgery.

During the operation, the surgeon reviews images of the planned outcome showing the relationship between the proximal and distal segments. Simultaneously, he manipulates a given proximal segment until the planned relationship is attained. This may involve resecting bone in areas of overlap and/or creating gaps between the segments. CASS facilitates these maneuvers by mapping and quantifying these areas in advance.

With genioplasty, surgeons can relocate the chin segment, either in freehand or with templates. The freehand method is the same as that described above for the mandibular proximal segment: the surgeon attempts to reproduce on the patient what is seen in CASS. The template method uses surgical templates to place the chin in its new alignment. Surgical templates are removable appliances that relocate and stabilize a non-dentate bony segment; they relate the planned position of the movable segment to adjacent segments.

Investigators at Houston Methodist Hospital in Texas developed the first known chin-template system (Figure 33).[10, 34] This system uses two templates: a marking template and a positioning template. Both relate the chin to the lower teeth. The marking template (Figure 33A and B) is employed first. It marks the position and orientation of two pilot-holes that are drilled on each side of the chin. After completion of the osteotomy, a surgeon places the positioning template (Figure 33C and D) on the lower teeth and aligns the chin to the template. The chin is then temporarily fixated to the template using two 2mm (diameter) screws, which are inserted through the template into the previously drilled pilot-holes. Next, the surgeon installs a chin plate for permanent stabilization; finally, the positioning template is removed.

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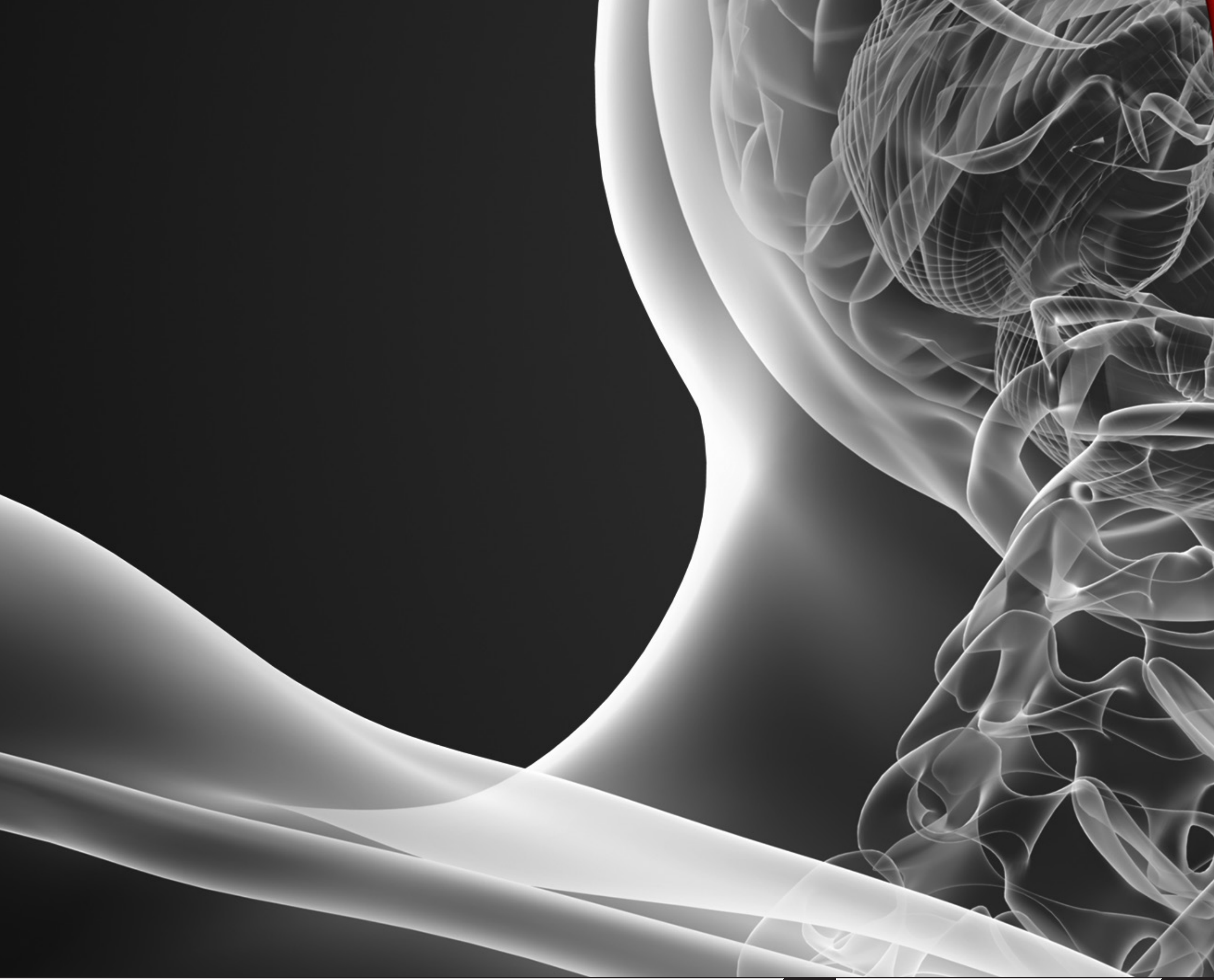

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