ONLINE SUPPLEMENT

A Two-Dimensional Model of Anatomic Relationships during Laryngoscopy

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Short title: 2-D Laryngoscopy Mannequin
This online supplement provides additional data about our two-dimensional model for studying laryngoscopy. We explain our reasoning behind the design and elaborate on many of the components. In addition, we discuss how the model was constructed and present the patterns for the individual pieces.

**Jaw**

The temporal mandibular joint consists of the articulation of the condyloid processes of the jaw with the glenoid fossae of the two temporal bones of the skull. The upper and lower surfaces differ considerably, resulting in a large amount of motion in anteroposterior, mediolateral and supero-inferior directions and rotation in several planes. The combined rotational-translational movement has proven difficult to model (1). Other investigators have approximated the joint with a single point hinge mechanism (1). We took the same path and added a sliding component to the hinge to account for supero-inferior rotation and allow the jaw to prognath along the long axis of the mandible (Figure S1). The pieces for the mandible and upper cranium were screwed together, with the mandible lying in a plane slightly higher than the cranial component. In order to avoid an offset between the upper and lower incisors, double thicknesses were included in the anterior portions of the maxilla and mandible. A piece having the same outline as the incisor and chin was aligned and attached underneath the front part of the mandible. A duplicate outline of the upper incisor, philtrum and nose was attached on the upper surface of the anterior maxilla. The double thicknesses on each side lined up with each other. The piece inserted under the mandible had a second function as a model for part of the tongue, explained in detail in a later section of this supplement.

With this design, the model emulates the most important motions for laryngoscopy in the sagittal plane, mouth opening and prognathation. In vivo, the mandible is anchored relatively loosely within the joint by a sling of muscles and can shift in the direction of any applied force, unlike the model. However, translation parallel to the axis of the mandible is the most likely
movement with the forward and upward lift of laryngoscopy. The length of the model jaw is 8.8 cm from angle to mentum, corresponding to a hyomental distance (HMD) of 6.2 cm. The front part of the jaw was constructed as a separate piece, connected by an adjustable bar to allow shortening to 8 cm (5.6 cm HMD) or lengthening to 10.1 cm (7.4 cm HMD). The mid face can be shortened or lengthened independently by a similar mechanism.

**Hyolaryngeal Complex**

The larynx can be divided into the supraglottis, the glottis, and the subglottis (2). The main laryngoscopic feature of the supraglottis is the epiglottis, which is cradled in the cul-de-sac formed by the hyoid bone. The epiglottis may vary but is usually slightly curved, with its concave surface facing posteriorly. In normal position, the laryngeal surface of the epiglottis droops toward the anterior commissure of the glottis.

During the process of laryngoscopy, the forces applied by the practitioner displaces the jaw and many parts of the anterior neck from their resting locations. Charters (1994) provided a good description of the course taken by the supraglottic structures during the process of laryngoscope blade insertion and subsequent lift (3). He noted that “before laryngoscopy the tongue is essentially in the mouth and the hyoid lies parallel to and just below the lower border of the mandible posteriorly. The insertion of a curved blade for laryngoscopy results in contact between the blade tip and the hyoid bone. [Upon lift], the hyoid bone is displaced anteriorly and downwards toward the larynx. It is also rotated on its body causing the greater horns to turn upward (3).” Marks et al. took radiographs during laryngoscopy to confirm that forward displacement of the hyoid bone by the laryngoscope blade tip elevates the epiglottis (4).

To accommodate these observations in our model design, we combined the epiglottis and hyoid in one piece with a hinge mechanism that allowed the two structures to rotate together in the sagittal plane (Figure S2). Forward, cephalad rotation (clockwise in the orientation of our model, moved the hyoid and epiglottis out of the way of the line of sight to
vocal cords. The model does not depict the greater horns of the hyoid. If they were present, laryngoscopy would rotate them cranially, as described by Charters (3).

The glottis is the elongated fissure between the inferior or true vocal cords in front, and between the bases and vocal processes of the arytenoid cartilages behind. The total length is approximately 20-25 mm in males (5). The portion below the true vocal cords widens out, and is continuous with the cricoid cartilage and trachea. The portion of the laryngeal cavity above the true vocal cords, the vestibule, is broad and triangular in shape, and corresponds to the interval between the alae of the thyroid cartilage. We made the assessment that the vestibule, the thyroid cartilage alae and the cricoid cartilage were not critical to the mechanics of laryngoscopy. We excluded them from the model to simplify analysis of the factors involved in visualizing the vocal cords. The model did include the inferior portion of the thyroid cartilage, measuring approximately 26 mm in length and 32 mm wide at its largest superior portion. A 15 mm line was scored at the cranial edge, representing the rima glottidis.

The average resting position of the laryngeal complex was based on anatomic reports and compared with literature cephalometric data as described in the print manuscript. The position of the larynx relative to other structures in the neck varies during growth and may also differ between normal individuals and patients with sleep apnea. Since laryngeal location could affect laryngoscopy difficulty, the larynx can be shifted over a 100 mm vertical and 70 mm horizontal range.

Cervical Spine

Movement of the cervical spine plays a critical role in determining access to the airway. It determines head position and is thus responsible for the alignment of oral, pharyngeal, and laryngeal axis necessary for successful laryngoscopy. Modeling of the cervical spine poses significant challenges because cervical spine is capable of more movement in all directions than
any other part of the spinal column (6). We will limit discussion to flexion and extension, the movement within the plane of the model.

The suboccipital region of the cervical spine consists of the axis, the atlas, and the occiput. Within this segment, flexion and extension takes place principally at the atlantooccipital joint, an enarthrosis in which the superior articular sockets of the atlas receive the condyles of the occiput. The union between the atlas and the head allows only for nodding movements between the two structures, and in all other respects the head and atlas move and function essentially as one unit (7). During flexion, the condyles roll forward and slide backward across the anterior walls of their sockets (if the condyles only rolled, they would roll up and over the anterior walls of their sockets (7). The combination of movements occurs in reverse during extension. The composite movement is a rotation or spin of each condyle across the surface of its socket. Thus, a point located on the lateral surface of the condyle will move anteriorly during the rolling component of flexion, and then slide posteriorly back to its original location during the posterior sliding component of flexion. Treating the atlantooccipital joint as a single-point hinge can closely approximate this movement. Figure S3 is an illustration of the design, showing a total range of motion of 26.6° in agreement with literature values, as described in the manuscript (8,9).

The inferior cervical segment, extending from the inferior surface of the axis to the superior surface of T1, is responsible for three-quarters of the total flexion and extension of the cervical spine (6). The axes of flexion and extension are through the posterior half of the vertebral bodies, and the movement of each of the intervertebral discs is approximately equal from level to level (10). As a rule, the cervical spine assumes a symmetrical lordosis in the neutral anatomical position (11). Figures 1 and 2 in the print manuscript display the CAD design of the cervical spine and a photograph of the model, respectively, showing the connecting points and lordosis incorporated into the design. We approximated each vertebral unit as a quadrilateral body with no attempt to represent lamina, spinous processes and other
specific details. As a result, horizontal dimensions are somewhat narrower than in the human cervical spinal column, but the vertical height is accurate, 120 mm between the inferior borders of C2 and C7 in neutral position, close to a distance of 117 mm measured in a patient (12).

The two-point hinge mechanism and the thickness and compliance of the foam rubber disks are key elements in establishing the realistic motion of the model. During flexion or extension, compression of rubber at the anterior or posterior edge of the disks limits how much movement is possible at each level. The rotation of the hinge also contributes to range of motion. **Figure 4** in the print manuscript shows the close correspondence of range of motion between real and model spines.

**Laryngoscope**

**Figure S4** illustrates the design of the laryngoscope, a Macintosh #3 blade following specifications from Penlon. A channel mounted on the side of the blade outlines the uppermost limit of the field of view that a practitioner would have during laryngoscopy.

**Tongue**

The tongue consists of four extrinsic muscles (genioglossus, hyoglossus, styloglossus, and palatoglossus) and four intrinsic muscles (superior and inferior longitudinal, transverse, and vertical). It lies partly in the oral cavity proper and partly in the pharynx, and at rest it occupies essentially the entire oral cavity proper. The origins of the extrinsic muscles include the superior part of the mental spine of the mandible (genioglossus), the body and greater horn of the hyoid (hyoglossus), the styloid process and stylohyoid ligament (styloglossus), and the palatine aponeurosis of the soft palate (palatoglossus). Thus, the mandible, tongue and hyoid are extensively linked.

The tongue is the only obstacle to a direct view of the larynx, and its disposition is critical to the ability to visualize the airway (3). The process of direct laryngoscopy displaces the tongue
to one side; inevitably a volume of tongue does not shift. This inevitable residual volume (IRV), as Charters termed it (3), must be accommodated between the laryngoscope blade and the mandible or in the space immediately below the mandible. The IRV would be larger and could obstruct the view during laryngoscopy if the tongue had reduced compliance or were disproportionately large.

Our model design, a two dimensional projection of the head and neck in the sagittal plane, could not accommodate lateral displacement of the tongue. Instead, the model focused on the portion of the tongue that was not displaced, the IRV. The plastic block inserted under the anterior portion of the mandible to align the incisors (see above) served double duty in representing the IRV. From inspecting radiographs taken during laryngoscopy, we estimated that tongue IRV would occupy roughly two-thirds the area of the anterior mandible and designed the block accordingly (Figure S5).

Laryngoscopy could be simulated by inserting the blade through the mouth underneath the posterior mandible. Recall from earlier that the mandible was raised because of the hinge mechanism. It was elevated off the backboard slightly greater than the thickness of the plastic from which the model pieces were cut. The IRV block prevented the blade from encroaching on the IRV space in the anterior mandible, just as compressed tongue would. The size of the block could be enlarged if we wanted to investigate the effects of a larger or less compliant tongue and we could also position barriers in the hypopharynx if desired.

**Design and Construction**

All collected data were first input into Smartsketch® version 4.0, a computer aided design program developed by Intergraph Corporation (Huntsville, AL). Patterns were drawn with our arrangement of the literature cephalometric data points (Figure S6). Since the large majority of available cephalometric data is in the metric format, data was initially input as metric and subsequently converted to standard units such that it was compatible with the remaining
software. Files were saved as AutoCad (*.dxf) while in the Smartsketch program, and were later transferred over to AutoCad 2000 Autodesk, Inc.

To construct the model, we employed the LaserCaMM™, a turnkey laser cutter that integrates fully with many types of CAD programs. Similar to a pen plotter, the system uses a laser beam to cut and scribe a variety of sheet materials into the design patterns. In order to use the LaserCAMM, the *.dxf file created from the CAD source was imported into the LaserCAMM Microsoft Windows™-based user software (LaserCAMM, version 11.0) and subsequently converted to a *.dmc file that is read by the machine. The laser beam thickness varies from .01” to .02”, depending on the thickness of the part to be cut. Thus, there exists the possibility that the shape cut will be slightly smaller than what has been designed in the software. Evaluation and testing from the LaserCAMM suppliers indicate the leadscrew resolution to be ± 0.005” per ft.

All parts constructed with the LaserCAMM software/hardware were constructed from 1/4” translucent acrylic. These include models of the cervical vertebral bodies, mandible, hyoid, laryngeal cartilages, teeth and cranium. Holes were tapped manually and round-head #6 Philips screws pieced the model into a functioning unit. In areas with adjustable features, plastic #6 thumbscrews could be used in place of the round-heads. The inter-vertebral disks were cut by hand from 1/4” flat foam-rubber using templates drawn in the Smartsketch program.

**Relationship between Handle Angle and Laryngoscopic View**

Over multiple laryngoscopy assessments with different anatomic configurations, here was a general relationship between angle taken by the Macintosh 3 laryngoscope hand, glottic view and hyoid displacement (Figure S7). When greater rotation of the laryngoscope occurred, lift of the hyoid (along with epiglottis) was greater and generally greater length of the glottic opening was visible.
References:


Figure Legends

Figure S1. Jaw range of motion. The drawing on the left demonstrates 5.9 cm maximum mouth opening in the model. The diagram to the right shows that the jaw wills prognath approximately 7 mm. The figure also illustrates the bars across the adjustable mandibular and maxillary components, giving the ability to alter the length of the face and jaw.

Figure S2. Design of the hyoid and epiglottis. A single point hinge allows the hyoid to move antero-inferiorly. Concomitant anterior rotation of the epiglottis would then reveal a line of sight to the vocal cords. Figure 2 in the journal article illustrates this point.

Figure S3. CAD representation of the atlantooccipital joint. The atlas and C1 are both in yellow. The atlantooccipital joint rotates as a single hinge (red circle) with 26.6° of motion in the sagittal plane. The blue lines represent the base of the skull. Extension corresponds to a leftward tilt (counter-clockwise) of the skull. The hinge by itself would allow too much flexion, shown by the rightward tilt. A block inserted anteriorly between the C1 and C2 vertebrae prevented the excess flexion.

Figure S4. Laryngoscope design. The pattern corresponds to a Penlon Macintosh 3 laryngoscope. Lengths are in mm.

Figure S5. Modeling the inevitable residual volume (IRV) of the tongue. A block of plastic, indicated by hatch marks, was inserted under the anterior mandible to limit the extent to which the laryngoscope blade could encroach into the mandibular space. In real life, part of the tongue would remain in this space and restrict the excursion of the laryngoscope, just as the block does in the model. The photograph is a cut-away view of the model featuring the mandible, anterior maxilla and larynx.

Figure S6. CAD patterns for the model components. The patterns of all of the acrylic parts of the model are shown drawn to scale. The patterns were produced with Smartsketch 4.0 and AutoCad 2000 computer aided design software. Parts were cut with the LaserCAMM, a turnkey laser cutter driven by CAD code.
**Figure S7. Relationship between handle angle, hyoid lift and glottic exposure.** The extent of lift of the model hyo-epiglottic complex was directly proportional to handle angle (left panel). Similarly, the handle angle bore a positive relationship with the glottic exposure (right panel). At less than 40° handle angle and 7 cm lift, no portion of the cords was in the field of view. These data reflect measurements made with mouth opening varying between 2 and 3.1 cm and mandible lengths between 8.2 and 9.4 cm.
Figure S1

Figure S2
Figure S3

Figure S4
Figure S5

- block occupying space for the tongue (IRV)
- maxilla
- laryngoscope
- hyoepiglottic complex
- coronoid and condyloid processes of mandible
Figure S6

Figure S7