# Intubation Biomechanics

## Laryngoscope Force and Cervical Spine Motion during Intubation with Macintosh and Airtraq Laryngoscopes

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### ABSTRACT

**Introduction:** Laryngoscopy and endotracheal intubation in the presence of cervical spine instability may put patients at risk of cervical cord injury. Nevertheless, the biomechanics of intubation (cervical spine motion as a function of applied force) have not been characterized. This study characterized and compared the relationship between laryngoscope force and cervical spine motion using two laryngoscopes hypothesized to differ in force.

**Methods:** Fourteen adults undergoing elective surgery were intubated twice (Macintosh, Airtraq). During each intubation, laryngoscope force, cervical spine motion, and glottic view were recorded. Force and motion were referenced to a preintubation baseline (stage 1) and were characterized at three stages: stage 2 (laryngoscope introduction); stage 3 (best glottic view); and stage 4 (endotracheal tube in trachea).

**Results:** Maximal force and motion occurred at stage 3 and differed between the Macintosh and Airtraq: (1) force: $48.8 \pm 15.8$ *versus* $10.4 \pm 2.8$ N, respectively, $P = 0.0001$; (2) occiput-C5 extension: $29.5 \pm 8.5$ *versus* $19.1 \pm 8.7$ degrees, respectively, $P = 0.0023$. Between stages 2 and 3, the motion/force ratio differed between Macintosh and Airtraq: $0.5 \pm 0.2$ *versus* $2.0 \pm 1.4$ degrees/N, respectively; $P = 0.0006$.

**Discussion:** The relationship between laryngoscope force and cervical spine motion is: (1) nonlinear and (2) differs between laryngoscopes. Differences between laryngoscopes in motion/force relationships are likely due to: (1) laryngoscope-specific cervical extension needed for intubation, (2) laryngoscope-specific airway displacement/deformation needed for intubation, and (3) cervical spine and airway tissue viscoelastic properties. Cervical spine motion during endotracheal intubation is not directly proportional to force. Low-force laryngoscopes cannot be assumed to result in proportionally low cervical spine motion. **(ANESTHESIOLOGY 2014; 121:260-71)**

ENDOTRACHEAL intubation in the presence of cervical spine instability is considered to put patients at risk of cervical spinal cord injury.[1–3] The concern is that, at an unstable cervical segment, the forces of conventional direct laryngoscopy may result in abnormally great (pathologic) motion of the unstable segment and result in cervical cord compression and injury. Although it is certain that cervical spine motion depends on amount of applied force, the *in vivo* relationship between laryngoscope force and resultant cervical spine motion has not been characterized. Hastings *et al.*[4] observed that direct laryngoscopy and intubation with a Miller laryngoscope blade required 30% less force and resulted in 30% less external head extension compared with that required in intubation with a Macintosh laryngoscope blade. This observation suggests that cervical spine motion during intubation may be directly proportional to the amount of applied force.

### What We Already Know about This Topic

- Video-laryngoscopy requires less cervical motion to accomplish tracheal intubation compared with that required by conventional direct laryngoscopy. We do not know whether the cervical motion is proportional to the force during laryngoscopy.

### What This Article Tells Us That Is New

- This randomized cross-over study simultaneously measured laryngoscope force and cervical spine motion during tracheal intubations with Macintosh and Airtraq laryngoscopes in anesthetized and paralyzed adult persons. The relationship between the force and motion was nonlinear and differed between the intubation devices. Notably, "low force" does not necessarily imply less cervical motion.

Several recent studies have shown that intubation with video-laryngoscopes that do not require a line of sight view of the glottis (*e.g.*, Airway Scope[5,6] [Pentax Europe GmbH, Hamburg, Germany], Airtraq[7,8] [Airtraq LLC, Fenton,

MO]) can be accomplished with 30 to 50% less cervical spine extension compared with conventional direct laryngoscopy with a Macintosh laryngoscope. For example, (1) Hirabayashi *et al.*[7] observed 29% less extension from the occiput (Oc) to the fourth cervical vertebrae (C4) (Oc-C4) with the Airtraq compared with the Macintosh during routine intubations; and (2) Turkstra *et al.*[8] observed 50% less extension from Oc-C5 with the Airtraq compared with the Macintosh during intubation with manual in-line stabilization. Accordingly, we hypothesized that if cervical spine motion is proportional to laryngoscope force, intubation forces with the Airtraq would be 30 to 50% less than that of the Macintosh.

The aim of this study was to measure and compare: (1) maximal laryngoscope force application; and (2) maximal segmental and overall (Oc-C5) cervical spine motion during orotracheal intubation with Macintosh and Airtraq laryngoscopes. We used these data to characterize the relationship between laryngoscope force application and resultant cervical spine motion and to determine whether motion/force relationships are linear and whether motion/force relationships differ between laryngoscopes.

## Materials and Methods

### Subjects

This study was conducted in accordance with the guidelines set forth by the University of Iowa Institutional Review Board for Human Subjects (Institutional Review Board #201102721, Iowa City, Iowa) and was registered with ClinicalTrials.gov (NCT01369381, registered June 7, 2011). All patients gave written informed consent before participation. The primary outcome measures were (1) maximal laryngoscope force application, and (2) maximal overall (Oc-C5) cervical spine motion (extension). On the basis of our previous studies, a cohort of 14 patients was projected to have an adequate power (two-sided $\alpha = 0.05$, $1-\beta = 0.80$) to detect differences as follows: (1) force application: 50% difference relative to control (Macintosh SD = 33 to 47%[9]); (2) Oc-C5 extension: 10 to 15% difference relative to control (Macintosh SD = 34%[10]).

Study patients were adults undergoing elective surgery requiring general anesthesia and oral endotracheal intubation in which C-arm fluoroscopy was to be used during the procedure. Inclusion criteria were intended to enroll patients who were likely to be easy to intubate with Macintosh-3 blade,[11–13] specifically: (1) Mallampati airway class I or II,[14] (2) thyromental distance of 6.0 cm or greater, and (3) sternomental distance of 12.5 cm or greater. Other inclusion criteria were (1) age 18 to 80 yr, (2) height between 1.52 and 1.83 m, and (3) body mass index of 30.0 kg/m² or less. Exclusion criteria (n = 19 criteria, complete list available) were intended to exclude patients who might be at increased risk of intubation and/or other study-related complications including (1) maxillary incisors that were loose or poor condition, (2)

previous difficult intubation, (3) any cervical spine anatomic abnormalities such as disc disease, instability, myelopathy, and/or any previous cervical spine surgery, (4) symptomatic gastroesophageal reflux or reactive airway disease, (5) any history of coronary artery disease or cerebral aneurysm, regardless of symptom status, (6) any history of vocal cord and/or glottic disease or dysfunction, (7) preoperative systolic blood pressure greater than 180 mmHg or diastolic blood pressure greater than 80 mmHg, and (8) American Society of Anesthesiologists physical status class greater than 3.

In consenting patients, preoperative head/neck morphology was characterized by: (1) interincisor distance, (2) jaw forward subluxation distance, (3) neck circumference, and (4) cervical offset distance.[15] Cervical offset distance is the distance between the posterior occiput and the wall in a standing patient whose head and neck are in neutral position, with their heels, buttocks, and back/shoulders in contact with a wall[15] (see Intubation Protocol). Consenting patients were assigned a study identification number to link them to a randomized intubation sequence.

### Randomization

Because each patient was intubated twice, using two different laryngoscopes, the sequence of laryngoscope use was randomized. The randomization scheme was a variable-size block design created to result in seven patients in each of the two intubation sequence groups by the end of the study. The randomization scheme was developed by an independent biostatistician and the scheme was unknown to the study investigators. Before patient enrollment, it was anticipated that intraoperative protocol failure was a possibility. Accordingly, the investigators had a pre-established plan to revise the randomization scheme in the event of a protocol failure. In the event of a protocol failure, all patient group assignments subsequent to and including the failure were discarded, and a new randomization scheme was created that would result in a final number of seven patients in each of the two groups. As described in Results, the sixth randomized patient was a protocol failure. Accordingly, after the six randomized patient, a new randomization scheme and new study envelopes were prepared and used for all subsequent patients (n = 9).

### Intubation Protocol

Each patient lay supine on a flat, level operating table. Neutral head and neck position was established by resting the patient's occiput on noncompressible pads at a height equal to their predetermined cervical offset distance.[15] In this position, and with the patient looking at the ceiling, a lateral cervical spine x-ray was obtained to serve as a preinduction neutral reference (stage 0).

Protocol-specific monitoring and anesthetics were used in all patients. Monitors included standard noninvasive respiratory and hemodynamic monitors, as well as electromyographic-based quantitative neuromuscular

transmission monitoring (S/5 Neuromuscular Transmission Module; Datex-Ohmeda Inc., Madison, WI), and electroencephalographic spectral entropy monitoring (E-ENTROPY module; Datex-Ohmeda Inc.). Before induction, midazolam was intravenously administered as needed (0 to 4 mg; mean ± SD = 0.03 ± 0.01 mg/kg). After at least 1 min of preoxygenation, general anesthesia was induced with intravenous lidocaine (0 to 1 mg/kg; 0.9 ± 0.1 mg/kg), fentanyl (0 to 2 µg/kg; 1.3 ± 0.6 µg/kg), and propofol (1 to 3 mg/kg; 2.3 ± 0.3 mg/kg), and mask ventilation with oxygen was established. The patient was ventilated with sevoflurane at greater than 1 to 2 inspired minimal alveolar concentration in oxygen followed by intravenous administration of rocuronium (0.70 mg/ kg; 0.68 ± 0.03 mg/kg). Thereafter, a sealed opaque envelope with the matching patient identification number was opened, revealing the randomized sequence of two intubations, either sequence 1: Macintosh intubation first and Airtraq intubation second; or sequence 2: Airtraq intubation first and Macintosh intubation second.

After induction of anesthesia, patients were mask ventilated for 3 to 5 min until both the following conditions were established: (1) end-tidal sevoflurane concentration was 1.5% or greater or the spectral entropy value was 70 or less; and (2) complete or near-complete pharmacological paralysis was established as indicated by the amplitude of the fourth twitch being 10% or less of the amplitude of the first twitch in response to a supramaximal stimulus of the ulnar nerve at the wrist (*i.e.*, train-of-four ratio of 0.1 or less). The study anesthesiologist then performed the first intubation using the laryngoscope indicated by the randomized sequence. After the first intubation, correct endotracheal tube position was verified and the patient was ventilated with sevoflurane in oxygen for 2 to 3 min. When hemodynamically stable, and when adequately oxygenated and ventilated, the patient was extubated and mask ventilation with sevoflurane was resumed. If needed, sevoflurane concentration was adjusted before the second intubation so that end-tidal sevoflurane concentration and/or entropy values again met criteria, but no additional muscle relaxant was given. Approximately 5 min after the first intubation, the second intubation was performed. After the second intubation, correct endotracheal tube position was verified and the protocol was complete. Surgery then proceeded.

All intubations were performed by two study anesthesiologists (B.J.H. and R.P.F.). In each patient, both intubations were performed by the same anesthesiologist. Each anesthesiologist intubated seven study patients; three patients with one sequence and four patients with the other sequence. Both anesthesiologists had more than 27 yr of postresidency experience with conventional direct laryngoscopy and intubation. Before this study, both anesthesiologists had performed at least 50 successful patient intubations with the Airtraq laryngoscope during the preceding year. This level of experience has been shown to be sufficient to achieve greater intubation success with an Airtraq than with a Macintosh in

patients with difficult airways.[16] In prestudy manikin studies, there were no significant differences between the two anesthesiologists in intubation times or forces with either laryngoscope (data available but not shown).

Before each patient use, the same reusable Macintosh-3 blade and both laryngoscope pressure sensor arrays (see Data Acquisition, Processing, and Analysis) were cleaned according to the standard clinical procedures used at the University of Iowa, which included exposure to 4% buffered glutaraldehyde. Each Airtraq intubation was performed with a new clean single-use size-3 ("Regular") Airtraq laryngoscope.

During Macintosh intubations, the distal tip of the laryngoscope blade was placed in the vallecula, followed by application of anterior-directed and slightly inferior-directed force to indirectly elevate the epiglottis, creating a direct line of sight between the glottis and superior aspect of the oral cavity. During Airtraq intubations, the distal tip of the laryngoscope was placed in the vallecula, followed by application of a largely anterior-directed force to elevate the epiglottis, placing the interarytenoid cleft in the lower half of the Airtraq video image.[17] During each intubation, anesthesiologists were tasked to achieve the best possible glottic view using only the laryngoscope. Manual head and neck movements were minimized and, if used at all, were limited only to that necessary to introduce the laryngoscope into the oral cavity. Once the laryngoscope was introduced, no external forces were applied to the head/neck or airway. By protocol, the occiput remained in contact with the underlying pad at all times. Use of an endotracheal tube stylet was permitted during intubations with the Macintosh laryngoscope. Patients were intubated with either a 7.0-mm (women) or 7.5-mm (men) inner diameter standard endotracheal tube. During each intubation, anesthesiologists verbally indicated when the laryngoscope was in its final position (best glottic view) immediately before endotracheal tube insertion. During each intubation, laryngoscope pressure sensor data, cervical spine motion (fluoroscopic digital video), and glottic view (airway camera digital video) were simultaneously recorded on a data acquisition computer; see Data Acquisition, Processing, and Analysis. The three data streams were electronically marked at "best view" as indicated by the anesthesiologist. Finally, after each intubation, anesthesiologists also verbally reported their observed glottic visualization using the percentage of glottic opening (POGO) score, corresponding to the percentage of the total distance between the anterior commissure and interarytenoid notch between the posterior cartilages.[18]

After surgery, all patients were evaluated for the presence of six predefined potentially study-related adverse events: (1) sore throat; (2) voice change; (3) voice pain; (4) swallowing difficulty; (5) dental damage; and (6) any other outcome as judged by the patient to be study related. Patients were evaluated in the recovery room, and on postoperative days 1, 3, and 7. When an in-person evaluation was not possible, a scripted phone interview was used. All patients had complete follow-up.

## Intubation Stages

For each intubation, laryngoscope force and resulting cervical spine motion were measured at each of the following predefined intubation stages:

**Stage 1—Preintubation Baseline.** Stage 1 was defined as the starting (baseline) occipital–cervical position immediately before each of the two intubations. This preintubation baseline image was obtained just before each intubation, after removing the ventilating mask and after allowing the head and neck to passively assume an unsupported resting position. Both laryngoscope force and intervertebral motion were defined as zero at this stage.

**Stage 2—Laryngoscope Introduction.** The laryngoscope was defined as being introduced when the leading edge of the laryngoscope was positioned inferior to the posterior tongue. This was considered to occur when the distal tip of the laryngoscope was seen at the inferior border of C2 based on a *post hoc* review of lateral fluoroscopic images (B.J.H and B.G.S.)

**Stage 3—Laryngoscope Placement ("Best View").** Stage 3 was defined as when the laryngoscope was in final position immediately before the endotracheal tube was placed in the glottis. This was determined *post hoc* by a review of simultaneous lateral fluoroscopic and laryngoscope video images (B.J.H. and B.G.S.), supplemented by the anesthesiologist's report of final position (best glottic view) immediately before endotracheal tube insertion.

**Stage 4—Intubation.** Stage 4 was defined as when the endotracheal tube had been advanced approximately 1 cm below the vocal cords. This was determined *post hoc* by a review of simultaneous lateral fluoroscopic and laryngoscope video images (B.J.H. and B.G.S.), supplemented by the anesthesiologist's report of intubation complete.

Intubation duration was defined as the interval between stage 1 and stage 4.

## Data Acquisition, Processing, and Analysis

**Laryngoscope Pressure and Force Measurement.** Laryngoscope blades were instrumented to measure applied pressures and forces. As shown in figure 1, custom-made 0.7-mm thick Pliance® pressure sensor arrays, enclosed with biocompatible high-strength polyurethane film (Novel Electronics Incorporated, Saint Paul, MN), were affixed to the contact surface of each laryngoscope using double-sided adhesive strips. The adhesive strips and sensor arrays were designed to perfectly match and completely cover the entire contact surface area of each laryngoscope. The Macintosh sensor array was 14.7 mm wide and 90 mm long and contained 27 independent pressure-sensing elements. The Airtraq sensor array was 19.6 mm wide and 110 mm long and contained 43 independent pressure-sensing elements. Each sensor in the array was capable of measuring applied pressures up to 1,500 mmHg (range, 0 to 1,500 mmHg; accuracy, 7.5 mmHg). During each intubation, pressures applied to the laryngoscope contact
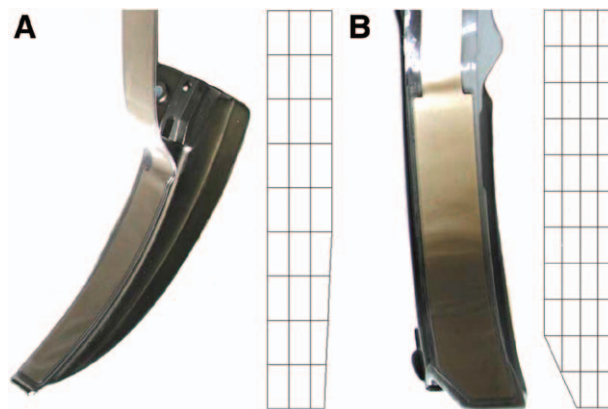


**Fig. 1.** Mounted sensor arrays and corresponding schematics showing individual sensing elements for (*A*) Macintosh and (*B*) Airtraq laryngoscopes.

surface were recorded using Pliance® Recorder software that allowed for simultaneous data capture and real-time display of each sensor's pressure (mmHg) and calculated force (N). Laryngoscope force was calculated as the sum of pressure measured by each individual pressure-sensing element multiplied by the individual sensing element's area. The center of pressure was also calculated and displayed in real time, defined as the location on the laryngoscope blade where the total sum of applied pressure acts on the sensor array, causing a force to act through that point (center of force). Between patient studies, sensor arrays were removed from the laryngoscope blades and stored flat. Each sensor array was calibrated at a minimum of every 3 months as recommended by the manufacturer. Calibration was accomplished by placing each array in a custom pressure chamber (Trublu®; Novel Electronics Incorporated) and applying known pressures between 0 and 1,500 mmHg, creating a 10-point calibration curve.

**Cervical Spine Intervertebral Motion.** During each intubation, cervical spine motion was monitored with continuous lateral C-arm fluoroscopy (OEC model 9800 Plus or 9900 Elite; General Electric OEC Medical Systems Inc., Salt Lake City, UT), affording visualization of the skull base, cranio-cervical junction, and cervical vertebrae through at least C5. By protocol, study-related total fluoroscopy exposure time was limited to no more than 90 s (both intubations combined). Exposure was adjusted to optimize visualization of the cervical spine. The fluoroscope was stationary throughout all imaging sessions. For each patient, the tube-to-patient and patient-to-image intensifier distances were constant throughout both intubations. The video signal of the fluoroscopy unit was interfaced to the data acquisition computer using an analog-to-digital video converter (Canopus ADVC110; Grass Valley USA, San Francisco, CA).

Intervertebral motion in the sagittal plane was measured by a single investigator (B.G.S.) in a similar manner to previous studies[7,8,10,19] using publically available image analysis software (NIH Image J, Bethesda, MD). For each

intubation, four single-frame fluoroscopic images corresponding to each of four predefined stages of intubation were selected; see Intubation Stages. On each of these four linked images, two landmarks were identified on each bony structure (Oc through C5) which were present in all four linked images. These landmarks served as fixed visual reference points to create a reference line on each vertebral body. The intersection of reference lines were then used to measure intervertebral angles at each of five intervertebral segments (Oc-C1, C1-C2, C2-C3, C3-C4, and C4-C5) at each of the four stages of intubation. Intervertebral motion during intubation was calculated as the change in intervertebral angles between stage 1 (the first baseline radiographic image of each intubation) and subsequent stages 2, 3, and 4. Extension was defined as positive values and flexion as negative values.

For each intubation, the assignment of visual reference points and intervertebral motion measurements were performed in three separate sets, with a minimum of 1 week between sets. Values from all three sets were combined to obtain a mean value that was used for statistical analysis. Intraobserver variation was calculated as the difference between corresponding intervertebral motion values among the three measurement sets ([14 patients × 5 segments × 3 stages × 2 laryngoscopes] × 3 sets = 1,260 paired observations). Intraobserver difference in intervertebral motion equaled $0.1 \pm 3.7$ degrees.

**Glottic View Airway Cameras.** During Macintosh intubations, best glottic view immediately before endotracheal tube insertion (stage 3) was recorded by means of an Airway Cam® (Airway Cam Technologies, Inc., Wayne, PA), which is a head-mounted video camera that records images in the laryngoscopist's line of sight.[20] In one of the 14 patients, an Airway Cam® image was not obtained during the Macintosh intubation. During Airtraq intubations, glottic view was recorded by means of a detachable Airtraq camera (Model ATQ-032). Airway Cam® and Airtraq camera video signals were interfaced with the data acquisition computer *via* a separate analog-to-digital video converter.

Glottic view video images corresponding to final position (best glottic view) immediately before endotracheal tube insertion (intubation stage 3) were analyzed off-line by a single unblinded investigator (B.J.H.). Glottic view was quantitated by use of POGO scores,[18] analyzed in two independent sets. Values from both sets were combined to obtain a mean value that was used for statistical analysis. Intraobserver variation in video-based POGO scores was calculated as the difference between corresponding video POGO scores in the two measurement sets ([14 patients × 2 laryngoscopes] – [1 missing Macintosh pair] = 27 paired observations). Intraobserver difference in POGO scores equaled $0 \pm 9\%$.

### Data Integration

Laryngoscope pressure sensor data, cervical spine motion (fluoroscopic digital video), and glottic view (airway camera digital video) were simultaneously recorded on a data acquisition computer. These three data streams were recorded at 30 Hz and were time synchronized using Pliance® Recorder software.

### Statistical Analysis

As described in Results, one patient (patient 6) was excluded from all data analysis because of a protocol failure. All statistical analyses were based on the 14 patients who completed the entire protocol. Outlier analysis was performed using Tukey method,[21] the modified Z-score method,[22] and Banerjee and Igelwicz's[23] method for small sample sizes. An observation was considered to be an outlier only when outlier conditions for all three methods were satisfied.

Continuous variables are reported as mean ± SD. Because of small sample sizes, we used more conservative distribution-free methods, using Analyse-it®, version 3.0 software (Analyse-it Software, Ltd., Leeds, United Kingdom). The Wilcoxon signed-rank test was used for pairwise comparisons and the Wilcoxon–Mann–Whitney test was used for nonpaired comparisons. Kendall Tau was used to test for associations. All *P* values are two-sided and exact. The threshold for statistical significance was *P* value less than 0.05, without adjustment for multiple comparisons.

## Results

One patient (patient 6, randomized to sequence 2) was withdrawn from the protocol after failure of the Airtraq light source, which precluded intubation with this device. The patient, the study Safety Officer, and the Institutional Review Board were notified of the protocol failure and the patient received full 7-day follow-up without adverse events. As described in Materials and Methods, a new randomization scheme was created to account for the protocol failure. All subsequent patients (n = 9) completed the study protocol, resulting in a total of 14 studied patients; sequence 1: Macintosh then Airtraq (n = 7), and sequence 2: Airtraq then Macintosh (n = 7).

Patient demographic and airway morphology characteristics are summarized in table 1. There was a sex imbalance in enrollment, with a greater number of women (n = 9, 64%) than men (n = 5, 36%), and a sex imbalance in intubation sequence assignment (sequence 1: women [n = 3], men [n = 4]; sequence 2: women [n = 6], men [n = 1]). Intubation characteristics are summarized in table 2. Intubation duration did not differ between laryngoscopes and, per protocol, end-tidal sevoflurane concentration and spectral entropy values immediately before each intubation did not differ between laryngoscopes. POGO scores at stage 3 were less during intubations with the Macintosh than with the Airtraq, based on both anesthesiologist report (*P* = 0.0007) and video analysis (*P* = 0.0002).

All intubations (14 patients × 2 intubations) were successfully performed except one in which there was an esophageal

**Table 1.** Patient Demographics and Airway Morphology

| Variable | Value (n = 14) |
|---|---|
| Sex | Women = 9 (64%), men = 5 (36%) |
| Age, yr | 47 ± 20 |
| Height, m | 1.68 ± 0.09 |
| Weight, kg | 73.5 ± 13.1 |
| Body mass index, kg/m² | 25.9 ± 3.4 |
| American Society of Anesthesiologists physical status class | 1 = 3 (21%), 2 = 11 (79%) |
| Mallampati oropharyngeal class | I = 8 (57%), II = 6 (43%) |
| Thyromental distance, cm | 6.9 ± 0.7 |
| Sternomental distance, cm | 18.1 ± 1.6 |
| Interincisor distance, cm | 5.0 ± 0.5 |
| Jaw subluxation distance, cm | 0.4 ± 0.3 |
| Neck circumference, cm | 37.0 ± 4.1 |
| Cervical offset distance, cm | 5.4 ± 2.3 |

Categorical values are expressed as n (%). Continuous values are expressed as mean ± SD.

**Table 2.** Intubation Conditions

| Variable | Macintosh (n = 14) | Airtraq (n = 14) | P Value |
|---|---|---|---|
| Intubation duration, s | 21.6 ± 7.8 | 19.6 ± 7.0 | 0.6698 |
| End-tidal sevoflurane concentration, % | 3.0 ± 1.4 | 2.5 ± 1.0 | 0.1763 |
| Spectral entropy value | 30 ± 10 | 32 ± 11 | 0.5186 |
| Percentage of glottic opening visualized at stage 3, % | | | |
|   Anesthesiologist verbal report | 74 ± 16 | 90 ± 10 | 0.0007 |
|   Video image analysis | 60 ± 15* | 92 ± 10 | 0.0002† |

Values are expressed as mean ± SD.

* n = 13. † P value based on 13 video pairs.

intubation with the Macintosh. This was immediately recognized and corrected without any adverse event. The data from this patient were included in the analysis. After surgery, all patients were evaluated for the presence of predefined study-related adverse events. On postoperative day 7, two patients (2 of 14; 14%) reported very mild voice changes that were intermittent and nonbothersome. There were no other patient reports of any other potential study-related adverse events at postoperative day 7.

Cervical spine position at the two preintubation baselines (*e.g.*, first intubation—stage 1 and second intubation—stage 1) differed from the preinduction supine neutral image (stage 0). This difference was likely due to mask ventilation. Specifically, when compared with the preinduction neutral image (stage 0): (1) before the first intubation, there was 8.8 ± 9.6 degrees of Oc-C5 extension, and (2) before the second intubation, there was 10.0 ± 11.4 degrees of Oc-C5 extension. However, cervical spine position at these two stage-1 baselines did not significantly differ from one another. Specifically, at Oc-C2, C2-C5, and Oc-C5, differences between the two intubations at stage 1 (second-first differences of 0.8 ± 5.5,

0.4 ± 3.7, and 1.2 ± 4.8 degrees of extension, respectively) were not statistically significant (*P* = 0.2166, 0.8077, and 0.1189, respectively), and these (non)-differences did not differ with intubation sequence (*P* = 0.2593, 0.9015, and 0.4557, respectively), sex (*P* = 0.3636, 0.8981, and 0.2977, respectively), or anesthesiologist (*P* = 0.3829, 0.0973, and 0.5350, respectively). Although starting (stage 1) cervical spine position did not significantly differ between first and second intubations, cervical spine motion that occurred during each intubation was referenced to the preintubation baseline (stage 1) position that existed immediately before that intubation.

Laryngoscope force application and cervical spine motion at intubation stages 2, 3, and 4 are reported in tables 3–5, respectively, and are summarized graphically in figure 2. At stage 2 (laryngoscope introduction), the Macintosh and Airtraq were essentially equivalent in the amount of applied force and in resultant cervical motion. Specifically, at stage 2, there was no difference between laryngoscopes in applied force (~3 ± 2 N). However, the center of force application was approximately 20 mm more distal (caudal) along the laryngoscope blade with the Macintosh than with the Airtraq, 41 ± 13 mm *versus* 61 ± 20 from the distal tip, respectively; *P* = 0.0203. At stage 2, extension at each intervertebral segment did not differ between the Macintosh and Airtraq except at C4-C5, 1.3 ± 2.0 *versus* –0.6 ± 1.8 degrees, respectively; *P* = 0.0295. When intervertebral segments were mathematically combined, at Oc-C2, both laryngoscopes resulted in equivalent degrees of extension (~6–7 ± 8 degrees;

**Table 3.** Laryngoscope Force Application and Cervical Motion at Stage 2—Laryngoscope Introduction

| Variable | Macintosh (n = 14) | AirTraq (n = 14) | P Value |
|---|---|---|---|
| Total force, N* | 2.8 ± 2.0 | 3.2 ± 2.0 | 0.7609 |
| Center of force, mm from distal tip of laryngoscope | 41 ± 13 | 61 ± 20 | 0.0203 |
| Intervertebral segment, degrees of extension | | | |
|   Oc-C1 | 3.8 ± 5.1 | 4.5 ± 5.0 | 0.4631 |
|   C1-C2 | 2.3 ± 3.9 | 2.3 ± 3.6 | 0.8077 |
|   C2-C3 | 0.5 ± 1.6 | 0.0 ± 1.6 | 0.2676 |
|   C3-C4 | 1.1 ± 2.9 | 0.6 ± 2.3 | 0.8552 |
|   C4-C5 | 1.3 ± 2.0 | –0.6 ± 1.8 | 0.0295 |
|   Combined Oc-C2 | 6.1 ± 8.4 | 6.8 ± 7.8 | 0.5830 |
|   Combined C2-C5 | 2.9 ± 4.2 | 0.0 ± 2.5 | 0.0295 |
|   Combined Oc-C5 | 9.1 ± 11.2 | 6.8 ± 8.9 | 0.5416 |
| Cervical motion (Oc-C5) change per unit of force change between stages 1 and 2, degrees/N | 3.6 ± 4.9† | 2.8 ± 4.5 | 0.1465‡ |

Values are expressed as mean ± SD.

* Percentage of all sensors in contact with tissue: Macintosh 41 ± 13%, Airtraq 33 ± 17%. † Macintosh group value excludes an outlier value from one patient (54.8 degrees/N) resulting from 13.4 degrees of motion with a force change of 0.245 N between stages 1 and 2. If the outlier value is included, Macintosh group value = 7.3 ± 14.5 degrees/N. ‡ Reported *P* value is based on paired comparison from 13 patients. If the Macintosh outlier value is included, *P* = 0.0785.

**Table 4.** Laryngoscope Force Application and Cervical Motion at Stage 3—Laryngoscope Placement (Best View)

| Variable | Macintosh (n = 14) | AirTraq (n = 14) | P Value |
|---|---|---|---|
| Total force, N* | 48.8±15.8† | 10.4±2.8‡ | 0.0001 |
| Center of force, mm from distal tip of laryngoscope | 35±6 | 46±13 | 0.0085 |
| Intervertebral segment, degrees of extension | | | |
| Oc-C1 | 11.4±6.5 | 9.6±4.5 | 0.1531 |
| C1-C2 | 8.1±4.7 | 5.5±4.8 | 0.1353 |
| C2-C3 | 2.4±3.0 | 1.8±3.6 | 0.4631 |
| C3-C4 | 5.1±3.7 | 2.0±3.3 | 0.0067 |
| C4-C5 | 2.5±3.5 | 0.2±2.6 | 0.1040 |
| Combined Oc-C2 | 19.6±10.3 | 15.1±7.4 | 0.0785 |
| Combined C2-C5 | 10.0±6.8 | 4.0±5.6 | 0.0031 |
| Combined Oc-C5 | 29.5±8.5§ | 19.1±8.7‖ | 0.0023 |
| Cervical motion (Oc-C5) change per unit of force change between stages 2 and 3, degrees/N | 0.5±0.2 | 2.0±1.4 | 0.0006 |

Values are expressed as mean ± SD.

* Percentage of all sensors in contact with tissue: Macintosh 95±7%, Airtraq 65±16%. † Women (n = 9): 41.1±13.4 N; men (n = 5): 62.6±9.2 N. ‡ Women (n = 9): 10.3±3.0 N; men (n = 5): 10.8±2.7 N. § Women (n = 9): 29.9±9.3 degrees; men (n = 5): 28.8±7.8 degrees. ‖ Women (n = 9): 23.6±7.6 degrees; men (n = 5): 11.2±2.5 degrees.

**Table 5.** Laryngoscope Force Application and Cervical Motion at Stage 4—Intubation

| Variable | Macintosh (n = 14) | AirTraq (n = 14) | P Value |
|---|---|---|---|
| Total force, N* | 43.6±13.5 | 6.5±2.0 | 0.0001 |
| Center of force, mm from distal tip of laryngoscope | 35±6 | 41±11 | 0.0785 |
| Intervertebral segment, degrees of extension | | | |
| Oc-C1 | 11.5±6.5 | 9.9±6.2 | 0.1937 |
| C1-C2 | 7.7±4.3 | 6.1±4.1 | 0.1937 |
| C2-C3 | 3.1±2.9 | 1.0±2.7 | 0.0245 |
| C3-C4 | 4.7±3.6 | 1.5±3.1 | 0.0245 |
| C4-C5 | 2.0±3.9 | 0.4±3.4 | 0.3910 |
| Combined Oc-C2 | 19.2±9.7 | 16.0±7.6 | 0.1726 |
| Combined C2-C5 | 9.8±6.5 | 2.8±6.0 | 0.0017 |
| Combined Oc-C5 | 29.0±8.7 | 18.9±9.2 | 0.0031 |
| Cervical motion (Oc-C5) change per unit of force change between stages 3 and 4, degrees/N | 0.3±1.0 | 0.3±1.3† | 0.6355‡ |

Values are expressed as mean ± SD.

* Percentage of all sensors in contact with tissue: Macintosh 94±7%, Airtraq 50±14%. † Airtraq group value excludes an outlier value from one patient (−1,349 degrees/N) which was the result of 2.7 degrees of motion with a force change of (−0.002 N) between stages 3 and 4. If the outlier value is included, Airtraq group value = −96±360.6 degrees/N. ‡ Reported P value is based on paired comparison from 13 patients. If the Airtraq outlier value is included P = 1.000.
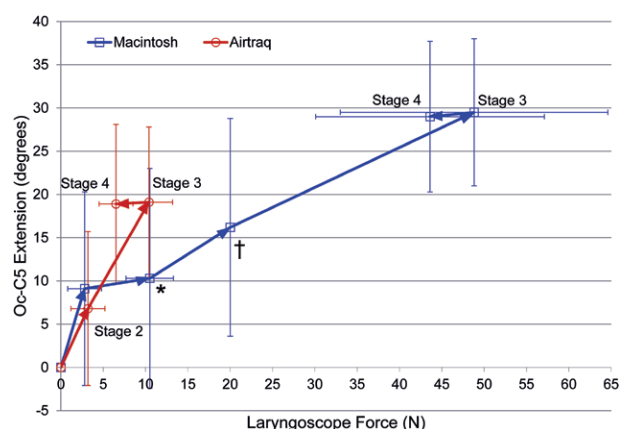


**Fig. 2.** Laryngoscope force and overall (Oc-C5) cervical spine extension for Macintosh (*blue square and lines*) and Airtraq (*red circle and lines*) laryngoscopes during the four stages of intubation: stage 1—preintubation baseline, defined as zero force and zero extension; stage 2—laryngoscope introduction; stage 3—laryngoscope placement ("best view"); and stage 4—intubation. *Macintosh Oc-C5 extension (10.3±12.7 degrees) at 10.4±2.8 N of force (see text). †Macintosh Oc-C5 extension (16.2±12.6 degrees) at 20.0±0 N of force (see text). Values are expressed as mean ± SD.

$P$ = 0.5830). In contrast, at C2-C5, there was greater extension with the Macintosh than the Airtraq, 2.9±4.2 *versus* 0.0±2.5 degrees, respectively; $P$ = 0.0295. Overall (Oc-C5) cervical extension did not differ between the Macintosh and Airtraq, 9.1±11.2 *versus* 6.8±8.9 degrees, respectively; $P$ = 0.5416. Between stages 1 and 2, the amount of Oc-C5 motion (degrees) that occurred per unit force applied by the laryngoscope (Newtons) was equivalent between the Macintosh and Airtraq, 3.6±4.9 *versus* 2.8±4.5 degrees/N, respectively; $P$ = 0.1465.

At stage 3 ("best view"), the two laryngoscopes differed in both the amount of applied force and resultant cervical spine motion. At stage 3, there was approximately a five-fold greater force applied with the Macintosh than with the Airtraq, 48.8±15.8 *versus* 10.4±2.8 N, respectively; $P$ = 0.0001. The Macintosh–Airtraq difference in applied force did not differ as a function of either anesthesiologist ($P$ = 0.3176) or intubation sequence ($P$ = 0.4557) but did differ as a function of patient sex ($P$ = 0.0070). Specifically, at stage 3, the Macintosh–Airtraq difference in applied force was greater in men than in women, 51.8±7.5 *versus* 30.9±12.5 N, respectively; $P$ = 0.0070. The center of force application was significantly more distal (caudal) along the laryngoscope blade with the Macintosh than with the Airtraq, 35±6 *versus* 46±13 mm from the distal tips, respectively; $P$ = 0.0085). At stage 3, extension at each intervertebral segment did not differ between the Macintosh and Airtraq except at C3-C4, 5.1±3.7 *versus* 2.0±3.3 degrees, respectively; $P$ = 0.0067. When intervertebral segments were mathematically combined, at Oc-C2, there was no difference in extension between the Macintosh and Airtraq, 19.6±10.3

*versus* 15.1 ± 7.5 degrees, respectively; *P* = 0.0785. In contrast, at C2-C5, there was greater extension with the Macintosh than the Airtraq, 10.0 ± 6.8 *versus* 4.0 ± 5.6 degrees, respectively; *P* = 0.0031. Overall (Oc-C5) cervical extension was greater with the Macintosh than that with the Airtraq, 29.5 ± 8.5 *versus* 19.1 ± 8.7 degrees, respectively; *P* = 0.0023. Macintosh–Airtraq differences in Oc-C5 extension did not differ as a function of anesthesiologist (*P* = 0.9015) but did differ as a function of both sex (*P* = 0.0420) and intubation sequence (*P* = 0.0379). Specifically, at stage 3, the Macintosh–Airtraq difference in Oc-C5 extension was greater in men than in women; difference = 17.6 ± 8.3 *versus* 6.4 ± 9.3 degrees, respectively; *P* = 0.0420. Also, the Macintosh–Airtraq difference in Oc-C5 extension was greater when the intubation sequence started with the Macintosh (sequence 1) compared with that when starting with the Airtraq (sequence 2); difference = 14.2 ± 13.1 *versus* 6.6 ± 4.8 degrees, respectively; *P* = 0.0379. Finally, there was a difference between the Macintosh and Airtraq in the relationship between applied force and overall (Oc-C5) motion. Between stages 2 and 3, the amount of Oc-C5 extension (degrees) that occurred per unit force (N) applied by the laryngoscope was four-fold less with the Macintosh than the Airtraq, 0.5 ± 0.2 *versus* 2.0 ± 1.4 degrees/N, respectively (*P* = 0.0006). Stated in other terms, between stages 2 and 3, for each degree of cervical extension, intubation with the Macintosh required four-fold greater force application than that required by the Airtraq. The Macintosh–Airtraq difference in the motion/force ratio was not affected by anesthesiologist (*P* = 0.9015), sex (*P* = 0.7972), or intubation sequence (*P* = 0.9015).

To further characterize the relationship between Macintosh force application and cervical spine motion, Oc-C5 motion was measured at two additional force values occurring between stages 2 and 3. Using each patient as their own control, the first additional Macintosh force value was equal to maximum Airtraq force applied at stage 3 (10.4 ± 2.8 N, range 5.4 to 13.8 N). The second additional Macintosh force value was equal to 20.0 N which was, in all patients, less than the maximum Macintosh force value at stage 3 (48.8 ± 15.8 N, range 23.8 to 70.9 N). As shown in figure 2, with the Macintosh, Oc-C5 extension equaled 10.3 ± 12.7 and 16.2 ± 12.6 degrees at 10.4 ± 2.8 and 20.0 ± 0.0 N of force, respectively. These intermediate values for Oc-C5 extension with the Macintosh seem to be on a nearly straight line between Macintosh values obtained at stages 2 and 3. With equivalent force (10.4 ± 2.8 N), Oc-C5 extension with the Macintosh (10.3 ± 12.7 degrees) was less than Oc-C5 extension with the Airtraq (19.1 ± 8.7 degrees); *P* = 0.0166.

Between stage 3 and stage 4 (intubation), laryngoscope force application significantly decreased with both the Macintosh (–5.2 ± 6.2 N, *P* = 0.0067; proportional change = –10 ± 10%) and the Airtraq (–3.9 ± 3.7 N, *P* = 0.0017; proportional change = –31 ± 33%). In contrast, between stages 3 and 4, Oc-C5 extension did not

significantly change with either laryngoscope; Macintosh (–0.5 ± 1.9 degrees, *P* = 0.4263), Airtraq (–0.3 ± 2.9 degrees, *P* = 0.6698), between stages 3 and 4, the amount of Oc-C5 motion that occurred per unit force did not differ between the Macintosh and Airtraq, 0.3 ± 1.0 *versus* 0.3 ± 1.3 degrees/N, respectively; *P* = 0.6355.

## Discussion

Our study confirms that cervical spine motion is affected by the amount of force applied by the laryngoscope but shows that intubation biomechanics are nonlinear and differ markedly between laryngoscopes. Although intubation with the Airtraq required only 20% of the force required by the Macintosh (~10 *vs.* ~50 N), it resulted in 67% as much Oc-C5 motion (~20 *vs.* ~30 degrees). Therefore, clearly, cervical spine motion is not simply linearly proportional to laryngoscope force. Anesthesiologists should not consider "low-force" laryngoscopes to necessarily result in proportionately less cervical spine motion.

### *Intubation Cervical Spine Motion and Force*

In our study, differences between the Macintosh and Airtraq in force application varied with patient sex, with greater Macintosh–Airtraq force difference in men. Sex-associated differences in laryngoscope force application have been reported by others, but these differences were not significant when weight and height were considered.[24,25] In our study: (1) men weighed more than women (88 ± 7 *vs.* 66 ± 8 kg, respectively; *P* = 0.0010), and (2) there was a positive association between patient weight and Macintosh–Airtraq force difference at stage 3 (*P* = 0.0101, Kendall Tau = 0.52, 95% CI = 0.24 to 0.79). Accordingly, in our study, it is likely sex-associated Macintosh–Airtraq force differences were due, at least in part, to sex-associated weight differences.

In our study, Macintosh–Airtraq differences in Oc-C5 extension depended on intubation sequence. At stage 3, the Macintosh–Airtraq difference in Oc-C5 extension was significantly greater when the intubation sequence started with the Macintosh (sequence 1) rather than starting with the Airtraq (sequence 2), 14.2 ± 13.1 *versus* 6.6 ± 4.8 degrees, respectively; *P* = 0.0379. However, because of the sex imbalance between the two intubation sequences, with a greater proportion of men in sequence 1 than in sequence 2 (4 of 7, 57% *vs.* 1 of 7, 14%, respectively), it is possible that apparent sequence-related Macintosh–Airtraq differences in Oc-C5 extension and force (sequence 1 > sequence 2) were due to sex-associated differences in these two factors (men > women).

### *Intubation Motion/Force Relationships*

Inspection of figure 2 shows that, in our study, during the first phase of intubation (stage 1 to 2), the relationship between force and Oc-C5 motion (the motion/force ratio, degrees/N) was the same with both laryngoscopes. However,

with additional force application (between stages 2 and 3), the two laryngoscopes diverged in the motion/force relationship. Although the motion/force ratio of the Airtraq remained the same as in the preceding stage, the motion/force ratio of the Macintosh decreased, indicating that a much greater amount of force was required to result in a unit (degree) of Oc-C5 motion. Because the biomechanical properties of the cervical spine and airway must be independent of the type of laryngoscope, we hypothesize that the observed divergence between laryngoscopes in the motion/force relationship may be on the basis of at least three non-mutually exclusive mechanisms.

The first potential mechanism for the divergence of laryngoscope motion/force relationships may be related to extension of the cervical spine toward anatomic maximum values. In a study of healthy young adults, Ordway et al.[26] reported maximal intervertebral extension from neutral equaled 14 degrees at Oc-C1, 5 degrees at C1-C2, and 9, 11, and 13 degrees at C2-C3, C3-C4, and C4-C5, respectively. Thus, in our study, at stage 3, it appears the Airtraq resulted in Oc-C2 extension (15.1 ± 7.4 degrees) that was near anatomic maximum (~19 degrees). Because Oc-C2 segments are near maximally extended with the low forces applied by the Airtraq, greater force application with the Macintosh could only result in a few additional degrees of extension (19.6 ± 10.3 degrees at stage 3). The result is a lesser value for the motion/force ratio with the Macintosh. In contrast, in subaxial segments (C2-C5), cervical extension with the Airtraq (4.0 ± 5.6 degrees) was much less than anatomic maximum (~33 degrees). In the subaxial (C2-C5) segments, with the greater force application of the Macintosh, cervical motion was, in fact, significantly (~2.5-fold) greater (10.0 ± 6.8 degrees) than with the Airtraq, while still being much less than anatomic maximum. Therefore, the observed decrease in the motion/force ratio with the Macintosh may be related, at least in part, to some intervertebral segments that were extended to near anatomic maximums during intubation (i.e., Oc-C2). However, this does not explain the overall (Oc-C5) Macintosh–Airtraq difference in the motion/force relationship between stages 2 and 3, because Oc-C5 extension with the Macintosh was less than that of the Airtraq at equivalent force values.

A second potential mechanism for the divergence of the motion/force relationships may relate to differences in how laryngoscope forces are distributed to and dissipated by tissues during intubation. In comparison to the Airtraq, much of the force applied by the Macintosh seems to contribute to processes other than cervical extension. Two such processes seem likely to be airway soft tissue (e.g., tongue) displacement/deformation and/or jaw subluxation. With conventional direct laryngoscopy, tongue displacement/deformation and/or jaw subluxation are necessary to create a line of sight.[27,28] In contrast, because of its shape and no need to create a line of sight, the need for tongue

displacement/deformation and/or jaw subluxation with the Airtraq is almost certainly much less. In our study, lateral x-rays demonstrated that anterior jaw subluxation was less with Airtraq (unpublished data: March 7, 2014, Bradley J. Hindman, M.D., Iowa City, IA, jaw anterior subluxation distance at stage 3). Therefore, differences between laryngoscopes in the proportion of total force contributing to airway displacement/deformation likely contribute to the observed divergence between laryngoscopes in motion/force relationships.

Finally, for both of these two laryngoscope-specific factors (required cervical extension, required tissue displacement), a third factor—tissue viscoelastic properties—determines the temporal relationship between force and motion/deformation. In the spine, the motion/force relationship becomes nonlinear when intervertebral segments approach anatomic maximum values.[29] In soft tissue, motion/force relationships are nonlinear, with greater displacement/deformation requiring disproportionately greater force.[30] As a combined result of these three factors, the relationship between laryngoscope force and cervical spine motion during intubation is nonlinear and differs between laryngoscopes.

The preceding discussion of intubation biomechanics is not complete. As illustrated in figure 3, other factors contributing to intubation biomechanics may also include anterior displacement of the cervical spine and skull, intervertebral anterior-posterior translation (minimal in the stable spine), friction, and gravitational effects (the weight of the head). In addition, strictly speaking, cervical spine motion during intubation is dependent on force-induced moments—the application of force over distance, and force vectors—the magnitude and direction of applied forces. Our study cannot determine the absolute or relative contributions of these other factors to intubation, but it is likely these also differ between laryngoscopes and contribute to differing motion/force relationships.

### Tissue Preconditioning

*In vitro* studies of isolated cervical spine segments[29] and soft tissues[30] show that because of tissue viscoelastic properties, motion/force relationships change over time and include a history effect (i.e., they are deformation cycle dependent). If major preconditioning effects had been present in our study, one would expect that Macintosh–Airtraq differences in force, motion, and motion/force ratios should differ as a function of intubation sequence. However, we observed no significant association between intubation sequence and either applied force (stage 3, $P = 0.4557$) or motion/force ratio (stage 2 to 3, $P = 0.9015$). These observations are consistent with the report by Hastings et al.,[4] who observed no difference in Macintosh intubation force (~44 N) in patients undergoing three sequential intubations by the same anesthesiologist. In our study, we observed an association between intubation sequence and Macintosh–Airtraq differences in Oc-C5 extension (stage 3, $P = 0.0379$). This
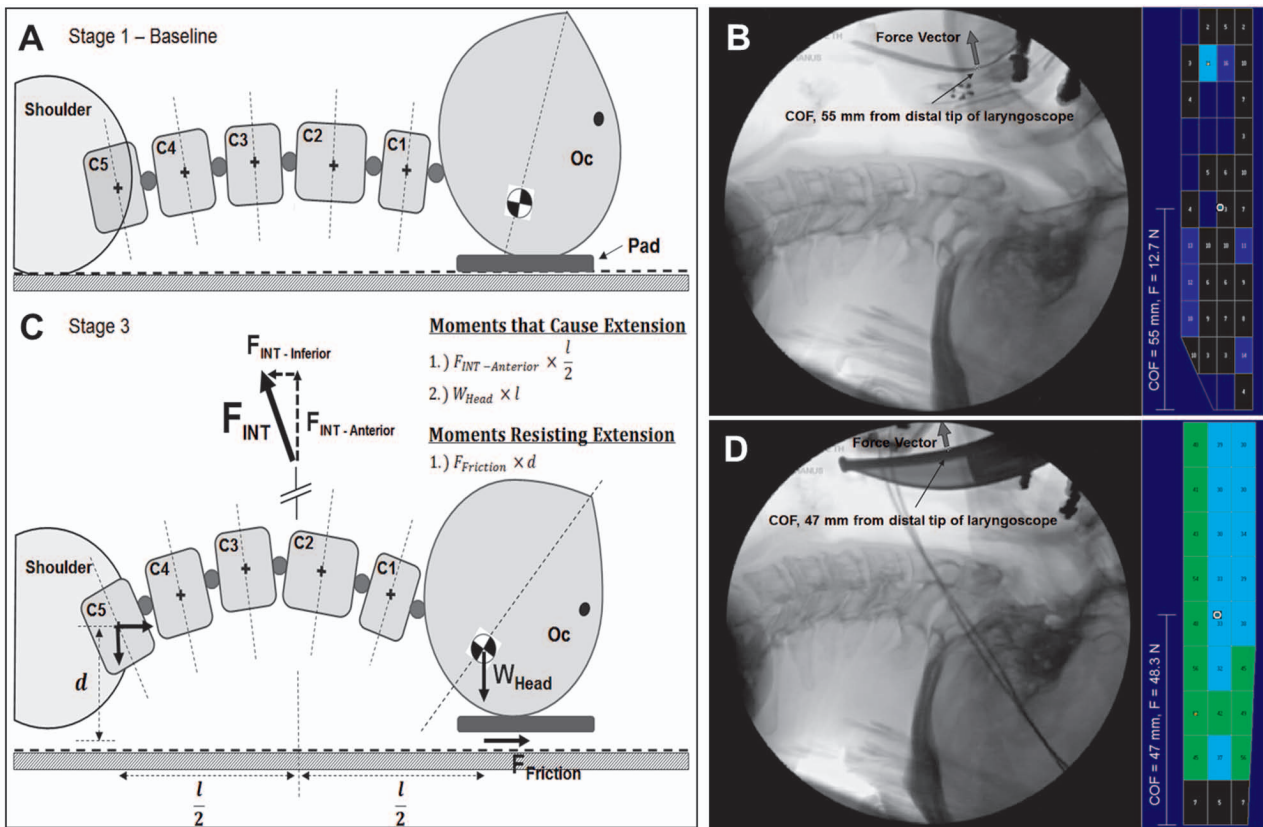
**Fig. 3.** (*A*) Schematic illustration of baseline (stage 1) position of the cervical spine (occiput to C5) before intubation. At this stage, the weight of the head ($W_{HEAD}$) and the force of gravity (⬤) keep the occiput resting on the pad. (*C*) During laryngoscopy (stage 3, "Best View"), the force of intubation ($F_{INT}$) is comprised of both inferiorly ($F_{INT-INFERIOR}$) and anteriorly directed forces ($F_{INT-ANTERIOR}$). Because $F_{INT-ANTERIOR}$ results in both airway tissue displacement/deformation and cervical spine motion, the amount of $F_{INT-ANTERIOR}$ transmitted to cervical spine is variably less than ($\nleftarrow$) total $F_{INT-ANTERIOR}$. During laryngoscopy, two predominant forces ($F_{INT-ANTERIOR}$ and $W_{HEAD}$) act across two distances from the C5 body ($l/2$ and $l$, respectively) to create two moments (moment = force × distance) in opposing directions that induce intervertebral rotation (extension). Increases in intervertebral rotation between stages 1 and 3 are qualitatively illustrated with *dashed lines* passing through each vertebral body and the occiput. The force of friction ($F_{FRICTION}$) between the pad and table acts at a vertical distance $d$ from C5, creating an opposing moment ($F_{FRICTION} \times d$) that acts to cause cervical spine flexion. (*B*) Lateral radiograph of a patient at intubation stage 3 with the Airtraq, with simultaneous laryngoscope force measurement (*inset*). The force vector (*bold arrow*, force (F) = 12.7 N) acts in a direction normal (90 degrees) to the laryngoscope surface through the center of force (COF, *small arrow*) located at 55 mm from the distal tip of the laryngoscope. (*D*) Lateral radiograph and force measurement at intubation stage 3 with the Macintosh in the same patient. The force vector (*bold arrow*, force (F) = 48.3 N) acts in a direction normal (90 degrees) to the laryngoscope surface through the COF (*small arrow*) located at 47 mm from the distal tip of the laryngoscope.

contrasts with the findings by Turkstra *et al.*[8] who reported Macintosh–Airtraq differences in cervical spine motion in patients who underwent laryngoscopy with both devices did not differ as a function of sequence. In our study, we cannot rule out that the apparent effect of sequence of Oc-C5 extension may have been due to the sex imbalance in intubation sequence assignment. Therefore, overall, in our study, we conclude that the effects of sequential intubations on intubation biomechanics were probably not significant.

### Study Limitations

A limitation of our study is that cervical spine motion analysis was performed by a single investigator who was not blinded to type of laryngoscope. In our study, motion analysis was

performed independently three times to minimize the effects of random outlier values and mean intraobserver variation was very small (0.1 degrees). Nevertheless, we acknowledge potential investigator bias cannot be excluded.

Another limitation of our study is that motion analysis took place only in the sagittal plane. Recently, two cadaver intubation studies used an electromagnetic motion analysis device to simultaneously quantify intervertebral rotations and translations in the sagittal plane (flexion–extension), coronal plane (lateral bending), and axial plane (axial rotation).[31,32] These studies showed that, during intubation, angulation occurred in all three planes, but that sagittal motion (extension) was the greatest.[31,32] This observation is consistent with other clinical studies.[33] In *in vitro* isolated

spinal segments, flexion/extension is the most sensitive load direction for disco-ligamentous instability.[34] Therefore, for endotracheal intubation, assessment of motion in the sagittal plane is the most clinically relevant, both when the cervical spine is stable and unstable.

Finally, all studies are susceptible to both type I and type II statistical errors. Because we did not adjust the threshold of statistical significance for multiple comparisons, it is likely that some of the apparent differences we report are, in fact, spurious. Nevertheless, for our primary outcome measures—maximal laryngoscope force and maximal Oc-C5 motion—differences between the Macintosh and Airtraq are sufficiently large and the associated $P$ values sufficiently small that our findings are highly likely to be reproducible.

### Summary

Intubation motion/force relationships are nonlinear and differ between laryngoscopes. These observations suggest that the following laryngoscope-specific factors contribute to the force/motion relationships (biomechanics) of intubation: (1) cervical extension needed for intubation, (2) airway tissue deformation needed for intubation, and (3) cervical spine and airway soft tissue viscoelastic properties. Because of these factors, cervical spine motion during endotracheal intubation is not linearly proportional to force.

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### Competing Interests

The authors declare no competing interests.

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