Intubation biomechanics: laryngoscope force and cervical spine motion during intubation in cadavers—effect of severe distractive-flexion injury on C3–4 motion

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Objective

With application of the forces of intubation, injured (unstable) cervical segments may move more than they normally do, which can result in spinal cord injury. The authors tested whether, during endotracheal intubation, intervertebral motion of an injured C3–4 cervical segment 1) is greater than that in the intact (stable) state and 2) differs when a high- or low-force laryngoscope is used.

Methods

Fourteen cadavers underwent 3 intubations using force-sensing laryngoscopes while simultaneous cervical spine motion was recorded with lateral fluoroscopy. The first intubation was performed with an intact cervical spine and a conventional high-force line-of-sight Macintosh laryngoscope. After creation of a severe C3–4 distractive-flexion injury, 2 additional intubations were performed, one with the Macintosh laryngoscope and the other with a low-force indirect video laryngoscope (Airtraq), used in random order.

Results

During Macintosh intubations, between the intact and the injured conditions, C3–4 extension (0.3° ± 2.7° vs 0.4° ± 2.7°, respectively; p = 0.9515) and anterior-posterior subluxation (−0.1 ± 0.4 mm vs −0.3 ± 0.6 mm, respectively; p = 0.2754) did not differ. During Macintosh and Airtraq intubations with an injured C3–4 segment, despite a large difference in applied force between the 2 laryngoscopes, segmental extension (0.4° ± 2.7° vs 0.3° ± 3.3°, respectively; p = 0.8077) and anterior-posterior subluxation (0.3 ± 0.6 mm vs 0.0 ± 0.7 mm, respectively; p = 0.3203) did not differ.

Conclusions

The authors’ hypotheses regarding the relationship between laryngoscope force and the motion of an injured cervical segment were not confirmed. Motion-force relationships (biomechanics) of injured cervical intervertebral segments during endotracheal intubation in cadavers are not predicted by the in vitro biomechanical behavior of isolated cervical segments. With the limitations inherent to cadaveric studies, the results of this study suggest that not all forms of cervical spine injury are at risk for pathological motion and cervical cord injury during conventional high-force line-of-sight intubation.

Key words

endotracheal intubation; cervical spine; cadaver; biomechanics

Laryngoscopy and endotracheal intubation in the presence of cervical spine instability are thought to put patients at risk for cervical spinal cord injury. Based on in vitro studies of isolated cervical segments, it is widely presumed that, with application of the forces of intubation, injured (unstable) segments will move more than normal, resulting in excessive stretch (e.g., via hyperextension) and/or direct compression (e.g., via subluxation) of the cervical spinal cord.

In a previous cadaveric study, we created an injured C1–2 segment (Type II odontoid fracture) and tested 3 hypotheses regarding the relationship between laryngoscope force and the motion of an injured cervical segment. Specifically, we tested whether, during endotracheal intubation, intervertebral motion of an injured cervical segment 1) was greater than that in the intact (stable) state, 2) differed when a high- or low-force laryngoscope was used, and 3) exceeded physiological values when greater levels of force were applied. Contrary to our expectations, none of these hypotheses was supported. A potential unifying
explanation for these unexpected findings was that the experimental injury (Type II odontoid fracture) was not sufficiently severe. It is conceivable that other intact supporting structures (e.g., bone, ligament, muscle) were sufficient to maintain the net stability of the injured C1–2 segment at a near-normal level.

Therefore, the aim of this experiment was to once again test these 3 hypotheses regarding motion-force characteristics of an injured cervical segment during endotracheal intubation but in the presence of a much more severe cervical spine injury. As in our previous studies, we used 2 laryngoscopes known to differ greatly in the amount of force they apply during intubation; specifically, we used a conventional high-force line-of-sight Macintosh laryngoscope and a low-force indirect video laryngoscope (Airtraq). In this experiment, we elected to study the motion of injured C3–4 intervertebral segments because 1) as a subaxial segment, C3–4 anatomy and kinematics differ significantly from those of the previously studied C1–2 segment and 2) to our knowledge, the motion of an injured C3–4 segment during intubation has not been previously studied.

**Methods**

**Cadaveric Specimens**

On the basis of our previous cadaveric study, in which intact C3–4 extension during Macintosh intubation equaled 2.1° ± 3.3°, a cohort of 14 cadavers was projected to have an adequate power (2-sided α = 0.05; 1 – β = 0.80) to detect a difference in C3–4 extension (intact vs injured) of 2.7°.

Fourteen cadavers were obtained from the Anatomical Gift Association of Illinois (Chicago). All the cadaveric specimens were unprepared and frozen until the day of study. Each specimen underwent external warming until the tissue temperature at 2 sites (posterior oropharynx and anterior or middle scalene muscle [0.5–cm depth]) was close to room temperature (at least 17°C according to a thermocouple thermometer [model 51 II], 80PJ-1 probe [Fluke]). After warming, the height, weight, airway morphology, and modified cervical offset distance of each cadaver were measured. For experiments, we modified the definition of cervical offset distance to equal the amount of occipital elevation necessary to establish head and neck neutrality in the supine (rather than the upright) position with the heels, buttocks, and back/shoulders of the cadaver in contact with a flat table. Before the study, neutral head and neck positions were established radiographically (by fluoroscopy), and the severity of preexisting cervical spine degenerative disease was rated by 2 neurosurgeons (R.B.F. and V.C.T.) using a validated 4-point ordinal scale.

**Intubation Methods**

For intubations, the cadaver was placed supine on a flat, level table with the occiput (Oc) resting on noncompressible pads at that cadaver’s previously established cervical offset distance. All intubations were performed by 2 faculty anesthesiologists (B.J.H. and R.P.F.), both of whom 1) had performed more than 50 successful patient intubations with the Airtraq laryngoscope and 2) had participated as the anesthesiologists in our previous clinical and cadaveric studies in which intubation biomechanics with Macintosh and Airtraq laryngoscopes were compared. In our previous clinical study, there were no systematic differences between these 2 anesthesiologists in intubation forces or cervical spine motion.

Each cadaver underwent 3 intubations. The first intubation was always performed in the presence of an intact cervical spine with a conventional reusable metal Macintosh-3 laryngoscope and a conventional malleable stylet (control measurements). Our previous clinical and cadaveric studies showed the average force application during intubation with a Macintosh laryngoscope to be approximately 50 N. After the first intubation, C3–4 injury was created (see “C3–4 Distractive-Flexion Injury”); thereafter (within 30 min), 2 additional intubations were performed in random order using 1) the same metal Macintosh-3 laryngoscope (with stylet) and 2) a single-use size-3 (regular) Airtraq video laryngoscope (~ 5 min between intubations). Our previous clinical and cadaveric studies showed the average force application during intubation with this indirect video laryngoscope to be ≤ 10 N. In each cadaver, all 3 intubations were performed by the same anesthesiologist using the same techniques described in our previous clinical and cadaveric study reports. Each cadaver was intubated with either a 7.0-mm (females) or a 7.5-mm (males) inner-diameter standard endotracheal tube.

During each intubation, the anesthesiologists were tasked with achieving the best possible glottic view using only the laryngoscope. Manual head and neck movement by the anesthesiologists was minimized deliberately and, if used at all, was limited only to what 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 (e.g., no manual stabilization, traction, cricoid pressure, etc.). Thus, intubations were performed to result in the greatest amount of cervical motion rather than to limit motion. During each intubation, the anesthesiologists verbally indicated when the laryngoscope was in its final position (resulting in the best glottic view) immediately before endotracheal tube insertion. During each intubation, laryngoscope pressure-sensor data (pressure arrays), cervical spine motion (fluoroscopic digital video), and glottic view (airway camera digital video) were recorded simultaneously on a data-acquisition computer (see “Data Acquisition, Processing, and Analysis”). These 3 data streams were electronically marked at intubation final position as verbally indicated by the anesthesiologists. After each intubation, the anesthesiologists also verbally reported observed glottic visualization using the percentage of glottic opening (POGO) score, which corresponds to the percentage of the total distance between the anterior commissure and interarytenoid notch between the posterior cartilages. Finally, after each intubation, the endotracheal tube was removed, and the head and neck were returned manually to (clinical) neutral position using the preestablished cervical offset distance of that cadaver.

During each intubation, laryngoscope force and resulting cervical spine motion were measured at each of the
following predefined intubation stages, which correspond exactly to those used in our previous clinical and cadaveric studies.8,9

Stage 1: Preintubation Baseline
Stage 1 was defined as the starting (baseline) occipital–cervical position immediately before the start of each intubation. Laryngoscope force and intervertebral motion were considered to be 0 at this stage.

Stage 2: Laryngoscope Introduction
Stage 2 was defined as when the distal tip of the laryngoscope was seen at the inferior border of C-2 based on a post hoc review of lateral fluoroscopic images (B.J.H. and B.G.S.).

Stage 3: Laryngoscope Placement (Final)
Stage 3 was defined as when the laryngoscope was in its final position immediately before the endotracheal tube was placed in the glottis, which 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 laryngoscope position 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, as determined by a post hoc review of simultaneous lateral fluoroscopic and laryngoscope video images (B.J.H. and B.G.S.), supplemented by the anesthesiologist’s report.

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

C3–4 Distractive-Flexion Injury
After the first (control) intubation, the cadaver was placed prone, and C3–4 injury was surgically created by 2 neurosurgeons (R.B.F. and V.C.T.). The injury was intended to simulate a severe (Stage 4) distractive-flexion type injury, such as that seen with bilateral facet dislocations.1 A midline posterior longitudinal cervical incision was made, and dissection was carried down to the lamina and articular processes. Fluoroscopy was used to verify the C3–4 level, and the supraspinous, interspinous, and posterior longitudinal ligaments, articular capsules, ligamentum flavum, and posterior annulus fibrosus were all transected. Then, using forced flexion, a complete bilateral C3–4 dislocation was created, and instability was verified radiologically (50% or more of the C-3 vertebral body was displaced anterior to the C-4 vertebral body), as shown in Fig. 1. The C3–4 dislocation was then reduced, the wound was closed in layers, and the cadaver was returned to the supine position for 2 additional intubations with C3–4 in the injured state.

Data Acquisition, Processing, and Analysis

Data Integration
Laryngoscope pressure-sensor data, glottic view (airway camera digital video), and cervical spine motion (fluoroscopic digital video) were recorded simultaneously at 30 Hz and were time synchronized using Pliance recorder software (Novel Electronics Incorporated).

Laryngoscope Pressure and Force Measurements
Macintosh and Airtraq laryngoscopes were instrumented to measure applied pressures and forces using the same methods as those in our previous studies.8,9 In brief, custom-made 0.7-mm-thick Pliance pressure-sensor arrays were affixed to cover the entire contact surface of each laryngoscope. During each intubation, the pressure applied to the laryngoscope contact surface was recorded using Pliance recorder software, which allowed for simultaneous data capture and real-time display of laryngoscope pressure (in mm Hg) and calculated force (in N). The center of applied pressure, defined as the location on the laryngoscope blade at which the total sum of applied pressure acts on the sensor array and causes a force to act through that point (center of force), was also calculated and displayed in real time. All sensor arrays were calibrated against known pressures, as recommended by the manufacturer.

Glottic View Airway Cameras

During Macintosh intubations, the glottic view present immediately before endotracheal tube insertion (Stage 3) was recorded by using an Airway Cam (Airway Cam Technologies, Inc.). 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 an analog-to-digital video converter (Canopus ADVC110).

Glottic view images from intubation Stage 3 of each of the 3 intubation conditions were analyzed offline by a single unblinded investigator (B.J.H.). The glottic view was quantitated by use of POGO scores,18 which were analyzed in 2 independent sets. Values from both sets were combined to obtain a mean value that was used for statistical analysis. Intraobserver variations in video-based POGO scores were calculated as the difference between corresponding video POGO scores in the 2 measurement sets; the mean (± SD) intraobserver difference was 1% ± 6%.

Lateral Fluoroscopy

During each intubation, cervical spine motion was monitored with continuous lateral C-arm fluoroscopy (OEC Model 9900 Elite; General Electric OEC Medical Systems), which captured views of the craniovertebral junction and cervical vertebrae through at least C-5. The video signal of the fluoroscopy unit was interfaced with the data-acquisition computer via a separate analog-to-digital video converter. In each cadaver, before each of the 3 intubations, a single-frame (“snapshot”) image of the Os and cervical spine, in which a 5/8th-inch-diameter metal sphere was placed in the midline just caudal to the men- tum, was obtained. This metal object served as a linear distance calibration standard for the subsequent image set. After obtaining this image, there were no changes in the distances between the x-ray source, cadaver, and image intensifier and no change in the angle of incidence between
the x-ray source and the spine during the subsequent intubation.

Cervical Spine Extension

Intervertebral extension was measured by a single investigator (B.G.S.) with publicly available image-analysis software (NIH Image J) using exactly the same methods used in our previous studies. In brief, the intersection of reference lines on each bony structure was used to measure intervertebral angles at each of 5 intervertebral segments (Occ–C1, C1–2, C2–3, C3–4, and C4–5) at each of the 4 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, considered to be 0°) and each of the subsequent intubation stages. A positive value indicated extension, and a negative value indicated flexion. For all intubations, cervical spine motion that occurred during each intubation was referenced to the preintubation baseline (Stage 1) position that existed immediately before each intubation. This method was the same as that used in our previous studies.

For each intubation, the assignment of visual reference points and intervertebral motion measurements were performed 3 times, with a minimum of 1 week between sessions. Values for each cadaver from all 3 sessions were combined to obtain a mean value that was used for statistical analysis. Intraobserver variations were calculated as the difference between corresponding intervertebral motion values among the 3 measurement sessions; the mean (± SD) intraobserver difference was 0.0° ± 1.9°.

Cervical Spine Canal Space

Space available for the cervical spinal cord at the level of the C3–4 disc during intubation Stage 3 was measured by a single investigator (R.B.F.) using publicly available image-analysis software (NIH Image J). Using each cadaver’s calibration standard, the following 3 straight-line distances were measured on each image of a set: 1) C-3 inferior endplate length; 2) anterior-posterior (AP) alignment of the C-3 and C-4 vertebral bodies; and 3) sagittal canal diameter at the level of the C3–4 disc space. First, in each cadaver, the Stage 1 C-3 inferior endplate length was used as a control measurement among the 3 intubations and served as an indirect index of C3–4 axial rotation and/or the angle of incidence between the x-ray source and the spine. If rotational differences among the 3 intubations are minimal, then one would expect C-3 endplate lengths to be identical in all 3 images. In this case, all linear distances in the sagittal plane should be consistent among all 3 image sets. Second, AP alignment of the C-3 and C-4 vertebral bodies was measured as the linear distance between 2 lines drawn along the anterior surface of both vertebral bodies. Positive values indicate that C-4 was anterior to C-3, and negative values indicate that C-4 was posterior to C-3. Third, C3–4 canal space corresponds to the smallest AP canal diameter at the level of the C3–4 disc space; therefore, in the presence of C3–4 subluxation, this location represents the site of maximum potential cord compression. When C-3 was displaced anteriorly, C3–4 canal space was measured as the distance between the posterior border of the C-4 vertebral body and the spinolaminar line of C-3. When C3 was posteriorly displaced, C3–4 canal space was measured as the distance between the posterior-inferior border of the C-3 vertebral body and the spinolaminar line of C-4. Here, we report 1) the change in C3–4 vertebral body alignment (subluxation) with intubation (Stage 3 vs Stage 1), 2) the change in C3–4 canal space with intubation (Stage 3 vs Stage 1), and 3) the absolute value of C3–4 canal space at Stage 3.

Statistical Analysis

Continuous variables are reported as means ± SD. All statistical analyses were performed using Analyze-it 3.90.6 software (Analyze-it Software, Ltd.). All p values are 2 sided and exact.

Patient values for intubation force and cervical spine motion came from original source data from Hindman et al. in which each patient underwent 2 intubations, 1 with a Macintosh laryngoscope and 1 with an Airtraq laryngoscope, in random order, using methods to measure laryngoscope force and cervical spine motion that were identical to those used in this cadaveric study.
For descriptive comparisons and characterization of control conditions, the Wilcoxon-Mann-Whitney test was used for unpaired comparisons (e.g., living patients vs cadavers), the Wilcoxon signed-rank test was used for pairwise comparisons, and the Friedman test was used for comparisons among the 3 intubation conditions.

The first null hypothesis was that there was no difference between the intact and the injured conditions with regard to 2 primary outcome measures (C3–4 extension and change in C3–4 AP vertebral body alignment [subluxation]) during intubations with the high-force (Macintosh) laryngoscope. The second null hypothesis was that, when the C3–4 segment was injured, there was no difference between the high-force (Macintosh) laryngoscope and low-force (Airtraq) laryngoscope with regard to the 2 primary outcome measures. Thus, a total of 4 hypotheses were tested using the Wilcoxon signed-rank test. Because all 4 p values were greater than 0.25, the threshold for significance was not adjusted for multiple comparisons.

**Results**

**Control Measurements**

**Intact Cervical Spine: Cadavers vs Patients**

The mean cadaver head/neck temperature was 23.3° ± 4.1°C. Cadaver demographic, airway morphology, and Macintosh intubation characteristics are summarized in Table 1 with corresponding values from our previous patient intubation study. Cadavers were older than the living patients. Although cadaver heights and weights were similar to those of patients, cadaver airway morphology differed from that of patients in a fashion that would be expected to increase the likelihood of difficult intubation. Moderate (n = 5) or severe (n = 3) cervical spine degenerative disease was present in 8 (57%) of 14 cadavers. Macintosh intubation duration and Stage 3 glottic visualization (based on both anesthesiologist verbal report and video analysis) were comparable between the patients and cadavers.

Macintosh laryngoscope force did not differ between patients and cadavers (~ 48 ± 20 N). In cadavers, extension of the segment of interest (C3–4) was less than that in patients (0.3° ± 3.0° vs 5.1° ± 3.7°, respectively; p = 0.0014; Hodges-Lehmann shift 5.3° [95% CI 1.7°–7.5°]). Extension at Oc–C2 did not differ between patients and cadavers (approximately 18.5° ± 10°). In contrast, C2–5 extension in cadavers was less than that in patients (p = 0.0004; Hodges-Lehmann shift 10.2° [95% CI 5.2°–14.2°]), and overall (Oc–C5) extension in cadavers was less than that in patients (p = 0.0091; Hodges-Lehmann shift 12.4° [95% CI 5.0°–19.5°]).

**Cadavers: Intact vs Injured C3–4 Segments**

In cadavers, control values for cervical spine extension (Oc–C5 and C3–4) did not differ among the 3 preintubation (Stage 1) baselines. Numerical values and all pairwise comparisons for these 5 control variables are available on request. Therefore, because 1) preintubation baseline cervical spine extension did not differ among the 3 experimental conditions and 2) preintubation C3–4 AP alignment and C3–4 canal space did not differ among the 3 preintubation baselines, C3–4 motion (extension and subluxation) and change in C3–4 canal space during intubation were compared among the 3 intubations.

**Primary Results: C3–4 Motion**

Intubation forces, glottic view, and motion of the intact and injured cervical spine during the Macintosh and Airtraq intubations are summarized in Table 2.

During intubations with an injured C3–4 segment, Macintosh laryngoscope force was slightly (~ 13%) less than that applied during intubations in the intact state (41.2 ± 21.4 N vs 47.1 ± 20.5 N, respectively; Hodges-Lehmann shift –8.6 N [95% CI –12.9 to –1.7 N]; p = 0.0353). Nevertheless, as shown in Table 2 and Fig. 2, during Macintosh intubations, 1) C3–4 extension did not differ between the intact and the injured conditions (0.3° ± 3.0° vs 0.4° ± 2.7°, respectively; p = 0.9515), and 2) the change in C3–4 vertebral body AP alignment (subluxation) did not differ between the intact and the injured conditions (~0.1 ± 0.4 mm vs ~0.3 ± 0.6 mm, respectively; p = 0.2754).

During intubations with an injured C3–4 segment, total intubation force was approximately 7-fold greater with the Macintosh laryngoscope than with the Airtraq laryngoscope (41.2 ± 21.4 N vs 5.5 ± 4.6 N, respectively). Nevertheless, as shown in Table 2 and Fig. 2, with injured C3–4 segments, 1) C3–4 extension did not differ between Macintosh and Airtraq intubations (0.4° ± 2.7° vs 0.3° ± 3.3°, respectively; p = 0.8077), and 2) change in C3–4 vertebral body AP alignment (subluxation) did not differ between intubations with a Macintosh laryngoscope and those with an Airtraq laryngoscope (~0.3 ± 0.6 mm vs 0.0 ± 0.7 mm, respectively; p = 0.3203). When the C3–4 segment was injured, extension was greater with the Macintosh than with the Airtraq laryngoscope, both at Oc–C2 (15.2° ± 9.2° vs 7.4° ± 5.6°, respectively; p = 0.0046) and C2–5 (2.2° ± 4.5° vs –1.8° ± 5.3°, respectively; p = 0.0295).

There were no differences among the 3 intubation conditions with regard to change in C3–4 canal space (approximately 0 ± 1 mm; p = 0.3951, Friedman test) or the absolute value of the C3–4 canal space (approximately 13 ± 2 mm; p = 0.0642, Friedman test). During Macintosh intubations in the injured state, the single greatest change in C3–4 AP alignment (subluxation), ~1.2 mm, resulted in a 0.7-mm decrease in C3–4 canal space to 11.3 mm. During Airtraq intubations in the injured state, the single greatest change in C3–4 AP alignment (subluxation), ~2.1 mm, resulted in a 2.5-mm increase in C3–4 canal space to a value of 14.9 mm. In the injured state, the smallest C3–4 canal values during Macintosh and Airtraq intubations were 10.1 and 10.4 mm, respectively.

**Discussion**

**Severe Distractive-Flexion Injury at C3–4**

In this study, we created a severe (Stage 4) distractive-flexion injury at C3–4. An injury of this severity would...
result in a subaxial injury classification (SLIC) score of 8–9 (maximum score of 10) and is associated with partial or total cord injury in almost all patients. To emulate the clinical scenario in which patients with such injuries would present most commonly for surgery, the C3–4 subluxation was reduced before intubation. Our control data show that C3–4 preintubation baseline (Stage 1) positions (intervertebral extension and AP alignment) were equivalent before all 3 intubations. We observed that 1) during high-force (Macintosh) intubations, the motion of injured C3–4 segments did not differ from that which occurred when the segments were intact, and 2) despite marked differences in total laryngoscope force, the motion of injured C3–4 segments did not differ between intubations with the Macintosh and those with the Airtraq laryngoscope. Thus, as with our previous cadaveric study, our hypotheses regarding the relationship between laryngoscope force and the motion of an injured cervical segment were not confirmed. Accordingly, we conclude that motion-force relationships (biomechanics) of injured cervical intervertebral segments during endotracheal intubation in cadavers are not predicted by the in vitro biomechanical behavior of isolated cervical segments.

In this experiment, before the creation of injury, intact cadaveric C3–4 segments exhibited less extension during intubation than previously observed in living patients.

**TABLE 1. Control measurements: demographics, airway morphology, cervical spine degeneration score, and Stage 3 Macintosh intubation conditions and cervical spine motion in patients and cadavers**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Patients (n = 14)</th>
<th>Cadavers (n = 14)</th>
<th>p Value (patients vs cadavers)</th>
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</thead>
<tbody>
<tr>
<td>Sex</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>9 (64)</td>
<td>9 (64)</td>
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</tr>
<tr>
<td>Male</td>
<td>5 (36)</td>
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<tr>
<td>Age (yrs)</td>
<td>47 ± 20</td>
<td>84 ± 8</td>
<td></td>
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<tr>
<td>Height (m)</td>
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<td>1.64 ± 0.08</td>
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<tr>
<td>Weight (kg)</td>
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<td>68.7 ± 10.4</td>
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<tr>
<td>Body mass index (kg/m²)</td>
<td>25.9 ± 3.4</td>
<td>25.4 ± 3.0</td>
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<tr>
<td>Mallampati oropharyngeal class</td>
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<td></td>
<td></td>
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<tr>
<td>I</td>
<td>8 (57)</td>
<td>NA‡</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>6 (43)</td>
<td>NA‡</td>
<td></td>
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<tr>
<td>Thyromental distance (cm)</td>
<td>6.9 ± 0.7</td>
<td>5.0 ± 0.5</td>
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<tr>
<td>Sternomental distance (cm)</td>
<td>18.1 ± 1.6</td>
<td>13.3 ± 1.6</td>
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<tr>
<td>Interincisor distance (cm)</td>
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<td>3.2 ± 0.8</td>
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<td>Jaw subluxation distance (cm)</td>
<td>0.4 ± 0.3</td>
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<td>Neck circumference (cm)</td>
<td>37.0 ± 4.1</td>
<td>35.0 ± 4.7</td>
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<td>Cervical offset distance (cm)</td>
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<td>Cervical spine degenerative disease class</td>
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<td>4</td>
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<td>3 (21)</td>
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<tr>
<td>Intubation duration (s)</td>
<td>21.6 ± 7.8</td>
<td>18.8 ± 8.6</td>
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<tr>
<td>POGO visualized (%) (anesthesiologist verbal report)</td>
<td>74 ± 16</td>
<td>66 ± 29</td>
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<tr>
<td>POGO visualized (%) (video image analysis)</td>
<td>60 ± 15</td>
<td>55 ± 22</td>
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<td>Total laryngoscope force (N)</td>
<td>48.8 ± 15.8</td>
<td>47.1 ± 20.5</td>
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</tr>
<tr>
<td>Center of force, mm from distal tip of laryngoscope</td>
<td>35 ± 6</td>
<td>36 ± 6</td>
<td></td>
</tr>
<tr>
<td>Intervertebral segment (° of extension)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3–4</td>
<td>5.1 ± 3.7</td>
<td>0.3 ± 3.0</td>
<td>0.0014</td>
</tr>
<tr>
<td>Combined Oc–C2</td>
<td>19.6 ± 10.3</td>
<td>16.9 ± 10.6</td>
<td>0.5112</td>
</tr>
<tr>
<td>Combined C2–5</td>
<td>10.0 ± 6.8</td>
<td>0.9 ± 4.3</td>
<td>0.0004</td>
</tr>
<tr>
<td>Combined Oc–C5</td>
<td>29.5 ± 8.5</td>
<td>17.9 ± 11.0</td>
<td>0.0091</td>
</tr>
</tbody>
</table>

NA = not applicable.
* Categorical values are numbers (%), and continuous values are means ± SD.
† All patient data were reported by Hindman et al. (2014).
‡ It was not possible to determine the Mallampati class reliably in cadavers.
§ Cervical spine degeneration scores (Côté et al.): 1 = absent or minimal osteophytosis; 2 = definite anterior osteophytosis, possible narrowing of the disc space, and/or some sclerosis of vertebral plates; 3 = moderate narrowing of the disc space, definite sclerosis of the vertebral plates, and/or osteophytosis; 4 = severe narrowing of the disc space, sclerosis of the vertebral plates, and/or multiple large osteophytes.
¶ Cervical spine degeneration scores were not assigned for patients.
Although cervical spine degenerative changes in our cadaver population might be the reason why C3–4 extension was less than expected when segments were intact (see additional discussion in “Limitations and Implications of Previous Cadaveric Intubation Studies”), degenerative changes cannot explain the near absence of C3–4 motion during intubations when segments were injured. In this study, the C3–4 injuries were severe; only the surrounding neck muscles and soft tissue were intact. Because we measured intubation forces, we know that Macintosh forces were nearly equivalent between intubations when the C3–4 segment was intact and those when the C3–4 segment was injured. Thus, the lack of difference in C3–4 segmental motion between the intact and the injured states during Macintosh intubations cannot be explained on the basis of a large difference in intubation forces between the 2 intubation types.

When the C3–4 segment was injured, despite marked differences in applied force between the Macintosh and Airtraq laryngoscopes, there was no difference in C3–4 motion, and motion at this interspace was negligible. Nevertheless, extension differences were present in other cervical segments (Oc–C2 and C2–5), and greater extension was found with the Macintosh. Thus, in this cadaver model, motion of the C3–4 segment (both extension and subluxation) seems to have been unaffected by laryngoscope force and C3–4 segmental stability. In all cadaver subjects under all conditions, the sagittal C3–4 canal space exceeded normal cervical spinal cord sagittal diameter at this level (approximately 6 ± 1 mm).13 Therefore, our results

### Table 2. Primary results for laryngoscope force application and C3–4 motion at Stage 3—laryngoscope placement (final), intact and injured C3–4 segments

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cervical Spine Condition, Laryngoscope</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intact, Macintosh (n = 14)</td>
<td>Injured C3–4, Macintosh (n = 14)</td>
</tr>
<tr>
<td>Total laryngoscope force (N)</td>
<td>47.1 ± 20.5</td>
<td>41.2 ± 21.4</td>
</tr>
<tr>
<td>POGO visualized (%) (video image analysis)</td>
<td>55 ± 22</td>
<td>61 ± 15</td>
</tr>
<tr>
<td>C3–4 extension (°)</td>
<td>0.3 ± 3.0</td>
<td>0.4 ± 2.7</td>
</tr>
<tr>
<td>C3–4 vertebral body AP alignment (mm)</td>
<td>−0.1 ± 0.5</td>
<td>0.1 ± 2.0</td>
</tr>
<tr>
<td>Change in C3–4 vertebral body AP alignment (subluxation) (mm)</td>
<td>−0.1 ± 0.4</td>
<td>−0.3 ± 0.6</td>
</tr>
<tr>
<td>Change in C3–4 canal space (mm)</td>
<td>0.0 ± 0.5</td>
<td>−0.4 ± 1.1</td>
</tr>
<tr>
<td>C3–4 canal space (mm)</td>
<td>14.1 ± 1.6</td>
<td>13.0 ± 1.9</td>
</tr>
<tr>
<td>Oc–C2 extension (°)†</td>
<td>16.9 ± 10.6</td>
<td>15.2 ± 9.2</td>
</tr>
<tr>
<td>C2–5 extension (°)</td>
<td>0.9 ± 4.3</td>
<td>2.2 ± 4.5</td>
</tr>
</tbody>
</table>

* Values are mean ± SD. Change values refer to changes between intubation Stage 1 (preintubation baseline) and Stage 3 (laryngoscope placement, final).
† Total number is 13.

**FIG. 2.** Primary results. **Left:** C3–4 extension values under each of the 3 following experimental conditions: intact cervical spine, Macintosh intubation; injured C3–4 segment, Macintosh intubation; and injured C3–4 segment, Airtraq intubation. **Right:** C3–4 subluxation values under each of the 3 following experimental conditions: intact cervical spine, Macintosh intubation; injured C3–4 segment, Macintosh intubation; and injured C3–4 segment, Airtraq intubation. Solid thick lines and dashed lines indicate means and standard deviations, respectively. Individual values are jittered to minimize graphic overlap and are connected by light-gray lines.
suggest that not all forms of cervical spine injury are at risk for pathologic motion and cervical cord injury during direct laryngoscopy intubation.

**Limitations and Implications of Previous Cadaveric Intubation Studies**

Similar to findings of our previous cadaver intubation study, in this new cadaveric study, with the Macintosh, 1) initial intubation force and Oc–C2 extension were comparable to those obtained in living patients, and 2) C2–5 extension was less than that of living patients. In this new cadaveric study, overall Oc–C5 extension was less than that of patients, whereas in our previous cadaveric study, it was marginally (but not significantly) less. Because in both of our studies cadaver subjects were quite old, we continue to think that the most likely explanation for lesser subaxial cervical extension in the cadavers is age-related degenerative changes in the cervical spine. These changes include disc degeneration, vertebral osteophytes, ligamentous calcification, and/or facet joint arthrosis or fusion. Age-related spondylosis is typically most severe in subaxial segments and/or facet joint arthrosis or fusion.

Of particular relevance to our study is that intact (stable) C3–4 extension during Macintosh intubation in cadavers was less than C3–4 extension previously observed in living patients (0.3° ± 3.0° vs 5.1° ± 3.7°, respectively), despite the application of equivalent intubation forces. Of the 6 previous cadaver intubation studies in which the motion of surgically injured subaxial segments during intubation was examined, only 1 study measured motion of the segment of interest during intubation in the intact state before injury creation. Specifically, Lennarson et al. reported a median baseline (intact) C4–5 extension of 0.8° with Macintosh intubation, a value that seems to be less than the C4–5 extension observed in living patients (2.5° ± 3.5°; 1.8° ± 3.6°, respectively). Therefore, previous cadaver intubation studies of injured subaxial segments likely had the same limitation that was present in our study—a low baseline (intact) motion in the segment of interest. These observations reinforce our previous conclusion that the motion-force characteristics of cadaver cervical segments cannot be automatically assumed to be the same as that of living patients, which calls into question the validity of cadaver intubation models.

We suggest that cadavers, at best, are imperfect models of human cervical spine biomechanics during endotracheal intubation. Factors that can affect the fidelity of cadaver intubation models include 1) cadaver age and age-related changes in cervical spine anatomy and range of motion, 2) the effect of different tissue-preservation methods on tissue biomechanics, 3) tissue temperature, 4) tissue recovery time, and 5) the effect of repeated intubations on tissue morphology, biomechanical properties (preconditioning), and intubation forces. These factors, either singly or collectively, might result in intubation motion-force characteristics (biomechanics) that differ substantially among cadaveric studies and, more importantly, differ from those of living patients.

Table 3 summarizes all previous cadaver intubation studies in which the motion of injured subaxial cervical spine segments were characterized during direct laryngoscopy, including data from this study. In none of these 7 cadaveric studies did intervertebral angulation (either flexion or extension) of unstable segments seem to exceed physiologically normal patient values. In fact, at the C3–4 and C4–5 segments, extension of injured cadaver segments during intubation did not seem to exceed the extension observed during intubation of patients with stable cervical spines. Similarly, in 5 of 7 cadaveric studies, subluxation of injured segments during intubation also did not appear to exceed physiologically normal patient values. However, 2 of 7 cadaveric studies found marked (pathological) segmental subluxation during intubation in the presence of severe C5–6 injury (4.8 mm [Donaldson et al.] and 5.7 mm [Prasarn et al.]). Because of the limitations of cadaver models, one cannot confidently accept or reject the findings of any single cadaveric study. Accordingly, there is need for more biomechanically reliable models of cervical spine motion and spinal cord integrity in the presence of cervical spine instability.

**Other Observations and Study Limitations**

Our current cadaveric study used fewer intubations and had less variation in cadaver tissue temperature and tissue-recovery intervals between intubations than in our previous study. Nevertheless, in our new cadaveric study, we again observed that Macintosh intubation force decreased with repeated intubations, and the mean decrease was approximately the same as that in our previous cadaveric study (approximately 8–9 N), which is consistent with tissue preconditioning and supports our previous conclusion that variations in tissue temperature and tissue-recovery intervals did not substantively affect our previous results. Likewise, in our current cadaveric study, intubation forces with the Airtraq (mean 5.5 N) were approximately 50% less than those required for intubation in living patients (mean 10.4 N) but were equivalent to those recorded after repeated intubations in our previous cadaver intubation study. Accordingly, we believe that the most likely cause of low (subclinical) Airtraq intubation forces in our cadavers is the result of the preceding (1 or 2) Macintosh intubations changing biomechanical properties of the cadaveric tissue (e.g., preconditioning).

Because the motion of the injured C3–4 segment was the same with the Macintosh and the Airtraq laryngoscopes, despite marked differences in laryngoscope force (Macintosh approximately 48 N, Airtraq approximately 5 N), we believe that it is very unlikely that Airtraq C3–4 motion would have been substantively different had clinically normal Airtraq forces been applied. For this reason, we did not use the “force-correction” methods that we used in our previous cadaveric study to estimate motion with the application of clinically normal Airtraq forces.

**Conclusions**

Our hypotheses regarding the relationship between laryngoscope force and the motion of an injured cervical segment were not confirmed. Motion-force relationships (biomechanics) of injured cervical intervertebral segments during endotracheal intubation in cadavers are not predicted by the in vitro biomechanical behavior of iso-
<table>
<thead>
<tr>
<th>Cervical Segment</th>
<th>Authors &amp; Year</th>
<th>Segmental Injury</th>
<th>No. of Subjects</th>
<th>MILS Used During Intubation</th>
<th>Segmental Angulation During Intubation (direction [°])</th>
<th>Segmental Subluxation During Intubation (mm)</th>
<th>Segmental Angulation During Intubation (direction [°])†</th>
<th>Segmental Subluxation, Maximum Voluntary (mm)‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3–4</td>
<td>This study</td>
<td>Intact (baseline)</td>
<td>14</td>
<td>No</td>
<td>Extension: 0.3 ± 3.0 (direction -0.1 ± 0.4)</td>
<td>Extension: 5.1 ± 3.7</td>
<td>Extension: 10.0 ± 5.6 (direction Flexion: 7.3 ± 3.8)</td>
<td>2.1 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Complete</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4–5</td>
<td>Lennarson et al., 2000§</td>
<td>Intact (baseline)</td>
<td>16</td>
<td>No</td>
<td>Extension: 0.8 (direction &lt;1)</td>
<td>Extension: 2.5 ± 3.5</td>
<td>Extension: 12.6 ± 5.2 (direction Flexion: 10.0 ± 6.4)</td>
<td>2.5 ± 0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incomplete, posterior</td>
<td>16</td>
<td>No</td>
<td>Flexion: 1.3</td>
<td>&lt;1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lennarson et al., 2001¶</td>
<td>Complete</td>
<td>10</td>
<td>No</td>
<td>Extension: 3.0 (direction 1.0)</td>
<td>Extension: 2.0 (direction 1.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turner et al., 2009</td>
<td></td>
<td>Complete</td>
<td>No effect</td>
<td>Extension: 2.5 (direction 0.4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5–6</td>
<td>Donaldson et al., 1993**</td>
<td>Incomplete, posterior</td>
<td>1–2</td>
<td>No</td>
<td>Extension: 7.5 (direction 4.8)</td>
<td>Extension: 3.9 (direction 12)</td>
<td>No data††</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lennarson et al., 2000§</td>
<td>Complete</td>
<td>14</td>
<td>Yes</td>
<td>Extension: 3.1 ± 1.2 (direction 2.2 ± 0.4)</td>
<td>Extension: 4.7 (direction 5.7)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MILS = manual in-line stabilization.

* Unless otherwise specified, values are mean ± SD or median. Unless otherwise specified, all data pertain to direct laryngoscopy and intubation performed with a Macintosh laryngoscope.

† Data for segmental angulation (extension) during intubation in patients with stable cervical spines as reported by Hindman et al. (2014).

‡ Data for segmental angulation (both flexion and extension) and subluxation during maximal voluntary motion in patients as reported by Wu et al. (2007). Segmental subluxation values are the sum of anterior subluxation during full flexion (~1 mm) and posterior subluxation during full extension (~1 mm).

§ In this 2000 study by Lennarson et al., posterior column elements were sectioned and facet joints were dislocated and then reduced. Values for segmental angulation are presented as the median, interpolated from their Figs. 3 (intact) and 5 (injury). MILS was used during intubation in the last 11 cadavers. In the presence of injury, the authors reported that flexion values did not differ between intubations with and without MILS, but no p value was reported. Values for segmental subluxation were not reported, but the authors stated that “in both the intact and partially destabilized states, A-P translation remained less than 1 mm.”

¶ In this 2001 study by Lennarson et al., cadavers were a subset of those studied previously in the authors’ 2000 study, in which additional (anterior column) injury was created and followed by additional intubations. Values are presented as the median, interpolated from Figs. 2 (angulation) and 3 (subluxation) in the 2001 study. The authors reported that extension values did not differ between intubations with and those without MILS, but no p value was reported. The authors reported that subluxation was greater with MILS (p < 0.05).

‖ In this study by Turner et al., complete anterior and posterior column injury was created, equivalent to that created by Lennarson et al. (2001). Intubations were performed with or without MILS, but the authors stated that the “application of MILS did not significantly change the median motion.” Thus, only pooled values were reported (i.e., data obtained without MILS and those obtained with MILS were combined). Values are presented as the median reported in the text and shown in Figs. 3A (angulation) and 3C (subluxation) in the Turner et al. study.

** In this study by Donaldson et al., the authors reported the “release of interspinous ligaments, facet capsule, ligamentum flavum, and posterior half of C5-6...” They did not specify if values were means or medians. Values are reported here as the increase in segmental motion when compared to intubation in the stable state, but stable state motion values are not reported. Stabilization was described as “in-line head stabilization.” During intubations with no stabilization, the extension value was derived from 1 cadaver, and the subluxation value was derived from 2 cadavers. Thus, statistical comparisons of motion (no stabilization vs stabilization) were not possible.

†† There have been no studies that specifically reported C5–6 motion during endotracheal intubation. In three studies by Turkstra et al. (2005, 2007, and 2009) in which Macintosh intubations were performed with MILS, mean motion between C-5 and an unmoving thoracic reference was reported to be 5°–8° of flexion.

‡‡ In this study by Gerling et al., the authors reported transection of anterior and posterior longitudinal ligaments, intervertebral discs, articular capsular ligaments, interspinous ligaments, and ligamentum flavum. The authors reported subluxation as a percentage of C-5 vertebral body width (11.1% ± 2.2%). With an estimated C-5 vertebral body width of ≤20 mm, subluxation was estimated to be ≤2.2 ± 0.4 mm.

§§ In this study by Prasarn et al., the authors reported transection of the supraspinous and interspinous ligaments, ligamentum flavum, facet capsules, the anterior longitudinal ligament, intervertebral discs, and the posterior longitudinal ligament. Values were reported in the text as means, but error bars in their figures were not defined. The authors reported angulation as “flexion/extension” and subluxation as “anterior/posterior translation” without specifying direction (e.g., flexion vs extension, anterior vs posterior subluxation). Thus, reported values may overestimate mean segmental motion if motion occurred in more than 1 direction.
lated cervical segments. The results of this study suggest that not all forms of cervical spine injury confer a risk of pathologic motion and cervical cord injury during conventional intubation. This finding is consistent with the great majority (but not all) of previous cadaver intubation studies that reported an absence of pathologic motion during endotracheal intubation in the presence of injured subaxial cervical segments. However, the limitations of cadaver models are such that it is not possible to determine which (if any) cadaveric studies reliably modeled the motion of injured cervical segments during endotracheal intubation in living patients.

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Cadaveric study of intubation with severe C3–4 injury


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Author Contributions
Conception and design: Hindman, Todd, Puttlitz, Santoni. Acquisition of data: all authors. Analysis and interpretation of data: Hindman, Fontes, Puttlitz, Santoni. Drafting the article: Hindman, Traynelis, Todd. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Hindman. Statistical analysis: Hindman. Administrative/technical/material support: Hindman. Study supervision: Hindman, Puttlitz, Santoni.

Supplemental Information
Previous Presentations
Portions of this work were presented in poster format at the Annual Meeting of the American Society of Anesthesiologists, San Diego, California, October 27, 2015.

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