Intubation Biomechanics

Laryngoscope Force and Cervical Spine Motion during Intubation in Cadavers—Cadavers versus Patients, the Effect of Repeated Intubations, and the Effect of Type II Odontoid Fracture on C1-C2 Motion

Bradley J. Hindman, M.D., Robert P. From, D.O., Ricardo B. Fontes, M.D., Ph.D., Vincent C. Traynelis, M.D., Michael M. Todd, M.D., M. Bridget Zimmerman, Ph.D., Christian M. Puttlitz, Ph.D., Brandon G. Santoni, Ph.D.

ABSTRACT

Background: The aims of this study are to characterize (1) the cadaver intubation biomechanics, including the effect of repeated intubations, and (2) the relation between intubation force and the motion of an injured cervical segment.

Methods: Fourteen cadavers were serially intubated using force-sensing Macintosh and Airtraq laryngoscopes in random order, with simultaneous cervical spine motion recorded with lateral fluoroscopy. Motion of the C1-C2 segment was measured in the intact and injured state (type II odontoid fracture). Injured C1-C2 motion was proportionately corrected for changes in intubation forces that occurred with repeated intubations.

Results: Cadaver intubation biomechanics were comparable with those of patients in all parameters other than C2-C5 extension. In cadavers, intubation force (set 2/set 1 force ratio = 0.61; 95% CI, 0.46 to 0.81; $P = 0.002$) and Oc-C5 extension (set 2 – set 1 difference = –6.1 degrees; 95% CI, –11.4 to –0.9; $P = 0.025$) decreased with repeated intubations. In cadavers, C1-C2 extension did not differ (1) between intact and injured states; or (2) in the injured state, between laryngoscopes (with and without force correction). With force correction, in the injured state, C1-C2 subluxation was greater with the Airtraq (mean difference 2.8 mm; 95% CI, 0.7 to 4.9 mm; $P = 0.004$).

Conclusions: With limitations, cadavers may be clinically relevant models of intubation biomechanics and cervical spine motion. In the setting of a type II odontoid fracture, C1-C2 motion during intubation with either the Macintosh or the Airtraq does not appear to greatly exceed physiologic values or to have a high likelihood of hyperextension or direct cord compression. **(Anesthesiology 2015; 123:1042-58)**

LARYNGOSCOPY and endotracheal intubation in the presence of cervical spine instability are considered to put patients at risk of cervical spinal cord injury.[1–3] However, only a single clinical study has formally reported cervical spine motion during intubation in the presence of an unstable cervical spine.[4] Instead, virtually all such studies have been performed in cadavers.[5–15] An important but unanswered question is whether cadavers are a valid biomechanical model of intubation. In our previous clinical study,[16] as well as in two other clinical studies,[17,18] intubation biomechanics in patients did not appear to be greatly affected by repeated (two) intubations. These observations differ from *in vitro* studies (nonliving tissue) in which motion/force relations change with repeated applications of force, particularly during the first few (one to three) load application cycles.[19,20] If repeated intubations change cadaver biomechanical properties, then cervical spine motion observed during the nth intubation could differ from what would be observed during the first intubation, potentially confounding the data.

What We Already Know about This Topic

- We lack scientific evidence whether laryngoscopy and tracheal intubation in patients with unstable cervical spine lead to spinal cord injury
- Validity of use of cadavers to investigate the possibility mentioned above has not been scientifically tested

What This Article Tells Us That Is New

- Biomechanics during laryngoscopy revealed similarity of laryngoscope forces and cervical spine motion between humans and cadavers
- Repeated intubation procedures changed biomechanics during laryngoscopy in cadavers
- In cadavers with a type II odontoid fracture, cervical motion during intubation with either the Macintosh or the Airtraq did not greatly exceed the range observed in intact cervical spines during the same procedures

Therefore, in experiment 1, we measured intubation forces and cervical spine motion in cadavers that underwent

intubations with two different laryngoscopes (*e.g.*, Macintosh and Airtraq [Airtraq LLC, USA]) and compared these values with those obtained in a prior clinical study in which patients underwent intubations with the same two devices.[16] In experiment 2, we determined whether cadaver intubation biomechanics changed with repeated (four to six) intubations.

In vitro, injured cervical segments exhibit a greater range of motion per unit force than when they are intact.[21] Accordingly, it is widely presumed that, with application of the forces of intubation, injured (unstable) segments will move more than normal, potentially resulting in excessive stretch (*e.g.*, *via* hyperextension) and/or direct compression (*e.g.*, *via* subluxation) of the cervical spinal cord and/or nerve roots. However, the relation between intubation force and the motion of an injured cervical segment has not been previously characterized. Therefore, the aim of experiment 3 was to test three hypotheses regarding the relation between laryngoscope force and the motion of an injured cervical segment. We hypothesized that, during endotracheal intubation, intervertebral motion of an injured cervical segment (1) would be greater than in the intact (stable) state; (2) would differ between high- and low-force laryngoscopes; and (3) would exceed physiologic values when greater levels of force are applied. To test these hypotheses, we created a type II odontoid fracture in cadavers and performed intubations with Macintosh and Airtraq laryngoscopes, which are known to differ in force and intervertebral motion.[16]

Materials and Methods

Cadaver Subjects

Fourteen cadavers were obtained from The Anatomical Gift Association of Illinois (Chicago, Illinois). All cadavers were unpreserved and frozen until the day of study. All cadavers underwent external warming until tissue temperatures at two sites (posterior oropharynx and anterior or middle scalene muscle [0.5 cm depth]) were both close to room temperature (at least 17°C, Thermocouple Thermometer [model 51 II], 80PJ-1 probe; Fluke Corporation, USA). After warming, cadaver height, weight, airway morphology, and modified cervical offset distance[22] were measured. For cadaver 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[22]) position, with cadaver heels,

buttocks, and back/shoulders in contact with a flat table. Before the study, neutral head and neck positions were established radiographically (lateral fluoroscopy), and the severity of preexisting cervical spine degenerative disease was rated by two neurosurgeons (R.B.F. and V.C.T.) using a validated 4-point ordinal scale.[23]

Intubation Methods

For all intubations, each cadaver was placed supine on a flat, level table with the occiput (Oc) resting on noncompressible pads at each cadaver's previously established modified cervical offset distance. All intubations were performed by two 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 over the preceding year and (2) had participated as the anesthesiologists in our prior clinical study comparing Macintosh and Airtraq laryngoscopes.[16] In our prior clinical study, there were no differences between these two anesthesiologists in intubation forces or cervical spine motion. Intubations were performed in paired sets, in which one intubation was performed with a reusable metal Macintosh-3 laryngoscope (with a conventional malleable stylet) and the other intubation with a single-use size-3 (regular) Airtraq laryngoscope in random order. In each cadaver, both intubations of a set were performed by the same anesthesiologist using the same techniques described in our prior clinical study.[16] Cadavers were intubated with either 7.0-mm (females) or 7.5-mm (males) ID standard endotracheal tubes.

During each intubation, anesthesiologists were tasked to achieve the best glottic view using only the laryngoscope. Manual head and neck movement by the anesthesiologist was deliberately minimized and, if used at all, was limited only when 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.*). During each intubation, anesthesiologists verbally indicated when the laryngoscope was in its final position (resulting in 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 simultaneously recorded on a data acquisition computer (see Data Acquisition, Processing, and Analysis). These three data streams were electronically marked at final position as verbally indicated by the anesthesiologist. After each intubation, the anesthesiologist also verbally reported best glottic view 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.[24] Finally, after each intubation, the endotracheal tube was removed, and the head and neck were manually returned to (clinical) neutral

position using the preestablished cervical offset distance of that cadaver.

For each intubation, laryngoscope force and resulting cervical spine motion were measured at each of the following predefined intubation stages[16]:

Stage 1—Preintubation baseline. Stage 1 was defined as the starting (baseline) occipitocervical position immediately before each intubation. Laryngoscope force and intervertebral motion were defined as zero 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 C2 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 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 verbal 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.

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 simultaneously recorded at 30 Hz and were time synchronized using Pliance® Recorder software (Novel Electronics Incorporated, USA).

Laryngoscope Pressure and Force Measurement. Macintosh and Airtraq laryngoscopes were instrumented to measure the applied pressures using the same methods used in our prior clinical study.[16] 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, pressures applied to the laryngoscope contact surface were recorded using Pliance® Recorder software that allowed for simultaneous data capture and real-time display of laryngoscope pressure (mmHg) and calculated force (N). The center of applied 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). All sensor arrays were calibrated against known pressures as recommended by the manufacturer.

Glottic View Airway Cameras. During Macintosh intubations, glottic view present immediately before endotracheal tube insertion (stage 3) was recorded by means of an Airway Cam® (Airway Cam Technologies, Inc., USA). During Airtraq intubations, stage 3 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 from intubation stage 3 were analyzed off-line by a single unblinded investigator (B.J.H.). Glottic view was quantitated by the use of POGO score,[24] which was 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 from experiment 1; mean (±SD) intraobserver difference was 1 ± 9%.

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 Inc., USA), visualizing the craniocervical junction and cervical vertebrae through at least C5. 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). In each cadaver, before each intubation set, a single-frame ("snap shot") image of the occiput and cervical spine was obtained in which a 6-mm diameter spherical metal object was placed in the midline of the posterior oral cavity. This metal object served as a linear distance calibration standard for the subsequent image set. After obtaining this image, the object was removed, with no changes in the distances between 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 paired (two) intubations of the set.

Cervical Spine Extension. Intervertebral extension was measured by a single investigator (B.G.S.) with publicly available image analysis software (NIH Image J, USA) using exactly the same methods used in our prior clinical study.[16] In brief, the intersection of reference lines on each bony structure was used to measure intervertebral angles at each of the five intervertebral segments (Oc-C1, C1-C2, C2-C3, C3-C4, and C4-C5) and 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, defined as 0 degrees) and subsequent stages. Extension was defined as positive values and flexion as negative values. As reported in Results, Experiment 1, Control Measurements, in cadavers, preintubation baseline (stage 1) cervical spine position differed between the first and second intubations. Accordingly, for all intubations in all experiments, cervical spine motion that occurred during

each intubation was referenced to the preintubation base-line (stage 1) position that existed immediately before each intubation. This was the same method that was used in our prior clinical study.[16]

For each intubation, the assignment of visual reference points and intervertebral motion measurements were performed three times, with a minimum of 1 week between sessions. Values for each cadaver from all three sessions 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 sessions; mean (±SD) intraobserver difference was 0.1 ± 3.2 degrees.

Cervical Spine Canal Space. In experiment 3 (see Experiments), space available for the cervical spinal cord in the sagittal plane at 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, three straight line distances were measured on each image of a set as shown in figure 1: (1) C2 inferior endplate length; (2) C2 canal space; and (3) C1–C2 canal space. First, in each cadaver, C2 inferior endplate length (anterior to posterior) was used as a control measurement among intubation sets, serving as an indirect index of C1–C2 axial rotation and/or the angle of incidence between the x-ray source and the spine. If rotational differences among intubation sets are minimal, then one should expect C2 endplate lengths to be identical in all images. In this case, all linear distances in the sagittal plane should be consistent among all image sets. Second, C2 canal space was used as a second control measure and was measured as the shortest distance between the posterior surface of the C2 vertebral body and the C2 spinolaminar line. The C2 canal space is a fixed bony space representing the space available for the cervical spinal cord that should be constant among all images and be unaffected by either intubation and/or C1–C2 injury. Third, the C1–C2 canal space corresponds to the smallest anteroposterior canal diameter at the C1–C2 level and, therefore, in the presence of C1–C2 subluxation, this location represents the site of maximum potential cord compression. As shown in figure 1, two C1–C2 canal space patterns were observed after the experimental C1–C2 injury (see Experiment 3, Type II Odontoid Fracture) and were measured as follows: (1) when the odontoid process was anteriorly displaced, C1–C2 canal space was measured as the distance between the posterior border of the C2 vertebral body (just caudad to the fracture line) and the spinolaminar line between C1–C2; (2) when the odontoid process was posteriorly displaced, C1–C2 canal space was measured as the distance between the posterior-inferior border of the odontoid process and the spinolaminar line between C1–C2. We report both the change in C1–C2 canal space with intubation (the change between intubation stages 1 and 3) and the absolute value of C1–C2 canal space at stage 3. In the presence of normal anatomy, C1 canal space (17 to 23 mm) is greater than C2 canal space (14 to 19 mm).[25–28] Accordingly, even in the event of C1–C2 subluxation and a decrease in C1–C2 canal space, as long as C1–C2 canal space remains greater than or equal to C2 canal space, the cervical spinal cord should not be compressed, with a critical lower value of 8 to 10 mm,[26,27,29–30]
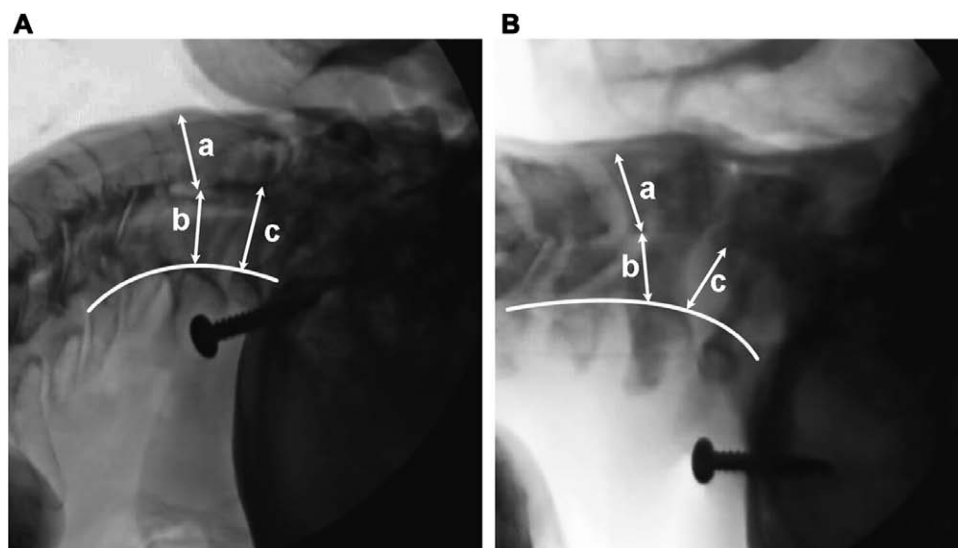
Fig. 1. Lateral fluoroscopy images demonstrating the methods to measure anterior-posterior spinal distances. (a) C2 inferior endplate length was measured as distance between the anterior and posterior surfaces of C2 at the inferior border of C2. (b) C2 canal space was measured as shortest distance between the posterior surface of the C2 vertebral body and the midpoint of C2 spinolaminar line. (c) C1–C2 canal space was defined as the smallest anterior-posterior distance available to the cord at this level, measured in one of two ways. As shown in *A*, when the C1-odontoid complex was anteriorly displaced, C1–C2 canal space (c) was measured between the posterior surface of the C2 vertebral body and the spinolaminar line between C1–C2. As shown in *B*, when the C1-odontoid complex was posteriorly displaced, C1–C2 canal space (c) was measured between the posterior-inferior surface of the odontoid and the spinolaminar line between C1–C2.

corresponding to the midline sagittal diameter of the cord at this level.[31,32]
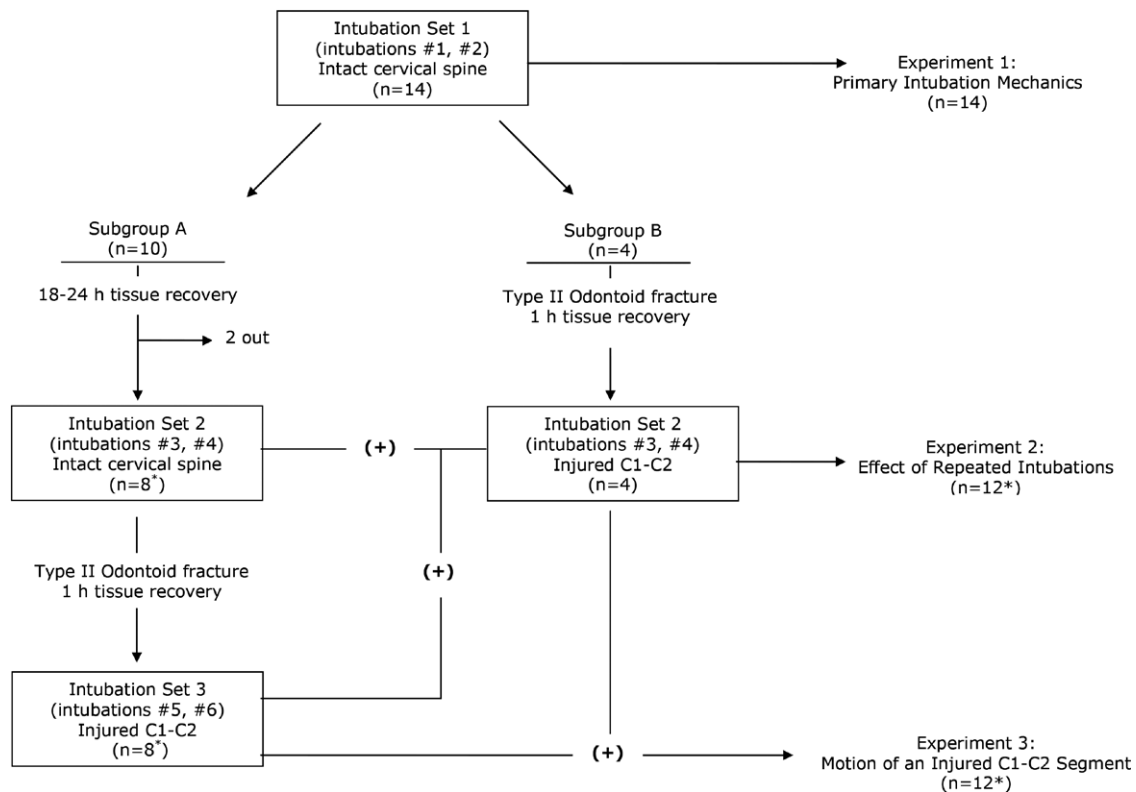
Experiments

A schematic summary of cadaver assignments, subgroups, and experiments is shown in figure 2.

Experiment 1: Primary Intubation Biomechanics. The aim of experiment 1 was to characterize cadaver intubation biomechanics with two different laryngoscopes and compare values to those previously obtained in patients. In prior clinical studies, coefficients of variation (SD/mean) of Macintosh intubation pressure[33] and cervical spine motion[34] were both 33%. A study population of 14 cadavers (this study) compared with 14 patients (from our prior clinical study[16]) provided sufficient power to detect the differences in mean Macintosh force and mean overall (Oc-C5) cervical spine motion of 18 N and 11 degrees, respectively (approximately 37% difference in mean values, unpaired t test, α = 0.05, 1-β = 0.80).

In experiment 1, each cadaver was intubated twice (intubation set 1: intubations 1 and 2), with each intubation performed using a different laryngoscope (Macintosh or Airtraq) in random order, with the constraint that an equal number of cadavers would be intubated with the Macintosh first (n = 7) and the Airtraq first (n = 7). Laryngoscope force application and overall (Oc-C5) cervical spine motion in cadavers were compared with patient values that were obtained using identical methods in our prior clinical study.[16]

Experiment 2: Effect of Repeated Intubations. The aim of experiment 2 was to determine whether intubation force and/or Oc-C5 extension changed with repeated intubations in the same cadaver. As described in Results, Experiment 1, marked airway tissue deformation was observed after intubation in some cadavers. Based on this finding, an *ad hoc*

Fig. 2. Cadaver assignments, subgroups, and experiments. In each cadaver, an intubation set consisted of two intubations, one with a Macintosh laryngoscope and another with an Airtraq laryngoscope in random order. All cadavers (n = 14) were included in Experiment 1: Primary Intubation Mechanics, wherein all intubations took place with an intact (stable) cervical spine. Thereafter, cadavers underwent additional studies in two subgroups: A (n = 10) and B (n = 4). Subgroup A underwent subsequent studies after an 18- to 24-h tissue recovery period. Two subgroup A cadavers could not undergo additional studies, leaving eight cadavers in subgroup A. Subgroup A cadavers underwent a second set of intubations with an intact cervical spine (set 2: intubations 3 and 4). After set 2 intubations, a type II odontoid fracture was created and a third set of intubations (set 3: intubations 5 and 6) were performed. In each subgroup B cadaver (n = 4), after set 1 intubations, a type II odontoid fracture was created, resulting in a 1-h tissue recovery period and, thereafter, cadavers underwent a second set of intubations (set 2: intubations 3 and 4). In Experiment 2: Effect of Repeated Intubations, data from subgroups A and B were pooled to compare intubation forces and cervical spine extension among intubation sets. In Experiment 3: Motion of an Injured C1-C2 Segment, data from subgroups A and B were pooled to compare C1-C2 motion between intact and injured states. *One subgroup A cadaver intubated only with Macintosh.

decision was made to perform additional experiments to characterize the effect of repeated intubations, allowing for two different tissue recovery intervals (two subgroups): long recovery (18 to 24 h, subgroup A; n = 10) and short recovery (1 h, subgroup B; n = 4). The tissue recovery interval (subgroup assignment) was not randomized but was determined *ad hoc* by cadaver, investigator, and laboratory availability.

Intubation Set 2 (Intubations 3 and 4). After completion of experiment 1, subgroup A cadavers (n = 10) were stored at 4°C overnight and underwent subsequent studies the next day without active rewarming, resulting in an 18- to 24-h tissue recovery period. Two subgroup A cadavers could not undergo the planned additional studies (equipment failure, airway deformation), leaving eight cadavers in subgroup A. Subgroup A cadavers underwent a second set of intubations with both Macintosh and Airtraq laryngoscopes (set 2: intubations 3 and 4) in the same intubation sequence as in experiment 1, although one subgroup A cadaver underwent intubations only with a Macintosh after set 1. In each subgroup B cadaver (n = 4), immediately after experiment 1, a type II odontoid fracture was created (see Experiment 3, Type II Odontoid Fracture), resulting in a 1-h tissue recovery period. Thereafter, subgroup B cadavers underwent a second set of intubations with both laryngoscopes (set 2: intubations 3 and 4) in the same sequence as in experiment 1. No additional studies were performed on subgroup B cadavers.

Intubation Set 3 (Intubations 5 and 6). In each subgroup A cadaver (n = 8), immediately after set 2 intubations, a type II odontoid fracture was created and a third set of intubations with both laryngoscopes (set 3: intubations 5 and 6) was performed. A new randomized sequence for the intubation order was used for set 3 intubations.

Force and Oc-C5 extension occurring during the three intubation sets were compared.

Experiment 3: Motion of an Injured C1-C2 Segment. The aim of experiment 3 was to characterize the motion of intact (stable) and injured C1-C2 segments to test three hypotheses regarding the behavior of injured cervical segments during intubation. Based on stable state C1-C2 extension observed during Macintosh intubations in patients (8.1 ± 4.7 degrees[16]), a sample of 12 cadavers was sufficient to detect a difference in Macintosh C1-C2 extension between intact and injured states of 4.2 degrees (approximately 50% difference in mean value; paired *t* test, α = 0.05, 1-β = 0.80).

Type II Odontoid Fracture. After stable state intubations were performed, a type II odontoid fracture[35] was created. An osteotome was inserted transorally and, under fluoroscopic guidance, was placed at the base of the odontoid process. A type II odontoid fracture was created and confirmed radiographically as described by Richter *et al.*[36] Thereafter, the head was returned to the clinically neutral position.

For primary analysis, data regarding the motion of the injured C1-C2 segment from subgroups A and B was pooled. Motion of the injured C1-C2 segment (set 3 for subgroup A; set 2 for subgroup B) was compared with C1-C2 motion

observed during the immediately preceding intubation set in which the C1-C2 segment was intact (set 2 for subgroup A; set 1 for subgroup B).

Calculation of Estimated "Force-corrected" Values. As reported in Results, Experiment 3, Primary Results, intubations in the presence of an injured C1-C2 segment occurred with laryngoscope forces that were less than the clinically normal values observed in initial (set 1) intubations. Accordingly, we speculated that observed motions of injured C1-C2 segments might be less than what would occur clinically. Therefore, we attempted to obtain estimates of motion of injured C1-C2 segments that would occur with the application of clinically normal intubation forces, which we refer to as "force-corrected" values of motion.

"Force-corrected" C1-C2 extension of each injured C1-C2 segment was calculated *post hoc* in two steps. First, for each observation with each laryngoscope, the extension/force ratio of the injured C1-C2 segment was calculated as shown in equation 1.

$$\text{C1-C2 extension/force}_{(INJURED\_C1-C2)} \\ = \text{C1-C2 extension}_{(INJURED\_C1-C2)} \\ \div \text{laryngoscope force}_{(INJURED\_C1-C2)} \quad (1)$$

Next, each value of C1-C2 extension/force$_{(INJURED\_C1-C2)}$ was multiplied by the corresponding laryngoscope force value measured during the first intubation (intubation set 1; clinically normal forces) to obtain "force-corrected" C1-C2 extension in the injured state as shown in equation 2.

$$\text{"Force-corrected" C1-C2 extension}_{(INJURED\_C1-C2)} \\ = \text{C1-C2 motion/force}_{(INJURED\_C1-C2)} \\ \times \text{laryngoscope force}_{(INTACT\_C1-C2, Set1)} \quad (2)$$

Similarly, *post hoc* "force-corrected" C1-C2 canal space of each injured C1-C2 segment was calculated in three steps. First, for each observation with each laryngoscope, the change in C1-C2 canal space (stage 3 – stage 1) per unit force of the injured C1-C2 segment was calculated as shown in equation 3.

$$\text{C1-C2 canal space change/force}_{(INJURED\_C1-C2)} \\ = \text{C1-C2 canal space change}_{(INJURED\_C1-C2)} \\ \div \text{laryngoscope force}_{(INJURED\_C1-C2)} \quad (3)$$

Next, each value of C1-C2 canal space change/force$_{(INJURED\_C1-C2)}$ was multiplied by the corresponding laryngoscope force value measured during the first intubation (intubation set 1) to obtain "force-corrected" C1-C2 canal change as shown in equation 4.

"Force-corrected" C1-C2 canal change

$$= \text{C1-C2 canal change/force}_{(\text{INJURED\_C1-C2})} \quad (4)$$
$$\times \text{laryngoscope force}_{(\text{INTACT\_C1-C2, Set1})}$$

Finally, "force-corrected" C1-C2 canal space was calculated by adding values for "force-corrected" C1-C2 canal change to preintubation baseline (stage 1) values of C1-C2 canal space as shown in equation 5.

$$\text{"Force-corrected" C1-C2 canal space} = \text{preintubation}$$
$$(\text{stage1}) \text{ C1-C2 canal space}_{(\text{INJUREDC1-C2})} \quad (5)$$
$$+ \text{"Force-corrected" C1-C2 canal change}$$

Statistical Analysis

Continuous variables are reported as mean ± SD. Outlier analyses were performed using Tukey method.[37] For descriptive comparisons and characterization of control conditions, the Wilcoxon signed rank test was used for pairwise comparisons and the Wilcoxon–Mann–Whitney test was used for nonpaired comparisons using Analyse-it®, version 3.0 software (Analyse-it Software, Ltd., United Kingdom).

Hypothesis testing in experiments 1, 2, and 3 used linear mixed-effect model analysis using SAS® 9.3 software (Statistical Analysis System Institute, Inc., USA). In all models, natural logarithm (ln) transformation of laryngoscope force was used to normalize the data distribution.

Experiment 1: Primary Intubation Biomechanics. Patient values for intubation force and cervical spine motion came from original source data from Hindman et al.,[16] in which patients underwent two intubations, one with a Macintosh and one with an Airtraq in random order, using methods to measure laryngoscope force and cervical spine motion that were identical to those used in this cadaver study. Cadaver values for intubation force and cervical spine motion used data from intubation set 1 (intubations 1 and 2). In addition to group (cadaver or patient, between-subject effect), the model included laryngoscope (Macintosh or Airtraq, within-subject effect) and the interaction between these two factors. The null hypothesis was that there was no difference between cadavers and patients with respect to two primary outcome measures (laryngoscope force and Oc-C5 extension) and four secondary outcome measures (motion/force ratio, Oc-C2 extension, C2-C5 extension, and center of force). Thus, in experiment 1, a total of six comparisons were made.

Experiment 2: Effect of Repeated Intubations. As described in Materials and Methods, Experiment 2, subgroups A and B differed in one or more of the following variables in a non-random manner: (1) tissue recovery time between intubation sets (18 to 24 h vs. 1 h); (2) tissue temperature ("room temperature" [approximately 21°C] vs. "cool" [approximately 7°C]); and (3) the condition of the C1-C2 segment (intact vs. injured). It was not possible to include any of these three variables as independent variables in the model because each was confounded by simultaneous differences in at least one of the other two variables. Therefore, the gestalt effect of these three variables was incorporated into the model by including subgroup (A or B) as a fixed effect between cadaver subjects. Other fixed effects included laryngoscope (Macintosh or Airtraq, within-subject effect), intubation set (1, 2, or 3, within-subject effect), and all interaction terms. The null hypothesis was that there was no difference among intubation sets with regard to two primary outcome measures (laryngoscope force and Oc-C5 extension). Using the estimates from the fitted mixed model, tests of mean contrast were performed to characterize differences between sets 1 and 2 and between sets 2 and 3 (subgroup A) for the two outcome measures. Thus, in experiment 2, a total of six comparisons were made.

Experiment 3: Motion of an Injured C1-C2 Segment. In the models, the condition of the C1-C2 segment (intact or injured) was a fixed effect within subjects. Subgroup, laryngoscope, and all interaction terms were included in the models as previously described. Using the estimates from the fitted models, tests of mean contrast were performed. The first null hypothesis was that there was no difference between intact and injured conditions with regard to two primary outcome measures (C1-C2 extension and change in C1-C2 canal space). The second null hypothesis was that, when C1-C2 was injured, there was no difference between the high-force laryngoscope (Macintosh) and low-force laryngoscope (Airtraq) with regard to the two primary outcome measures. Thus, in experiment 3, a total of four comparisons were made.

In experiment 3, the two null hypotheses were tested using primary experimental data and also using "force-corrected" data.

Thresholds for Significance. All P values are two sided and exact. Each experiment (1, 2, and 3 [without and with "force correction"]) was considered to constitute an independent set of hypotheses. To account for multiple comparisons within each experiment, the threshold for statistical significance was adjusted using the Benjamini–Hochberg false discovery rate control procedure set at a 5% level.[38]

Results

Experiment 1: Primary Intubation Biomechanics

Cadaver demographic, airway morphologic, and intubation characteristics are summarized in table 1, with corresponding values from our prior patient intubation study.[16] Cadavers were older than patients. Although cadaver heights and weights were similar to those of patients, cadaver airway morphology differed from that of patients in a manner that would be expected to increase the likelihood of difficult intubation.[39,40] Moderate (n = 5) or severe (n = 3)[23] cervical spine degenerative disease was present in 8 of 14 (57%) cadavers.

Table 1. Experiment 1: Demographics, Airway Morphology, Cervical Spine Degeneration Score, and Intubation Conditions in Cadavers and Patients

Variables	Cadavers, Intubation Set 1 (n = 14)	Patients (n = 14)*
Sex	Women = 9 (64%), men = 5 (36%)	Women = 9 (64%), men = 5 (36%)
Age, yr	85 ± 6	47 ± 20
Height, m	1.68 ± 0.11	1.68 ± 0.09
Weight, kg	67.2 ± 16.5	73.5 ± 13.1
Body mass index, kg/m²	23.6 ± 5.1	25.9 ± 3.4
Mallampati oropharyngeal class	†	I = 8 (57%), II = 6 (43%)
Thyromental distance, cm	4.9 ± 0.9	6.9 ± 0.7
Sternomental distance, cm	14.6 ± 1.6	18.1 ± 1.6
Interincisor distance, cm	3.0 ± 0.8	5.0 ± 0.5
Jaw subluxation distance, cm	0.2 ± 0.3	0.4 ± 0.3
Neck circumference, cm	33.5 ± 5.5	37.0 ± 4.1
Cervical offset distance, cm	3.1 ± 2.1	5.4 ± 2.3
Cervical spine degenerative disease class‡	1 = 3 (21%), 2 = 3 (21%), 3 = 5 (36%), 4 = 3 (21%)	§
Intubation duration, s		
Macintosh	17.5 ± 6.1	21.6 ± 7.8
Airtraq	21.6 ± 7.4	19.6 ± 7.0
Percentage of glottic opening visualized at stage 3, % (video image analysis)		
Macintosh	56 ± 18‖	60 ± 15‖
Airtraq	93 ± 11	92 ± 10
Percentage of glottic opening visualized at stage 3, % (anesthesiologist verbal report)		
Macintosh	75 ± 24	74 ± 16
Airtraq	88 ± 7	90 ± 10

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

* All patient data were previously reported by Hindman et al.[16] † It was not possible to reliably determine Mallampati class in cadavers. ‡ Cervical spine degeneration scores[23]: 1 = absent or minimal osteophytosis; 2 = definite anterior osteophytosis, possible narrowing of the disc space, some sclerosis of vertebral plates; 3 = moderate narrowing of the disc space, definite sclerosis of the vertebral plates, osteophytosis; 4 = severe narrowing of the disc space, sclerosis of the vertebral plates, multiple large osteophytes. § Cervical spine degeneration scores not assigned in patients. ‖ n = 13.

In experiment 1, cadavers were intubated twice, once with each laryngoscope in random order. By coincidence, the sex imbalance in intubation order in cadavers was the same as in our prior patient study.[16] In cadavers, intubation duration did not differ between laryngoscopes, and glottic visualization at stage 3 was greater with the Airtraq than with the Macintosh, based on both video analysis and anesthesiologist verbal report. These findings in cadavers are comparable with those made in patients.

Experiment 1: Control Measurements. In experiment 1 cadaver head/neck temperature was 21.4° ± 3.0°C. Cervical spine position at the two preintubation baselines differed from one another. Specifically, at Oc-C2 and Oc-C5, differences between the two preintubation baselines (second-first differences) equaled 4.0 ± 3.7 (P = 0.0009) and 3.3 ± 3.2 (P = 0.0002) degrees of extension, respectively. These differences did not vary with intubation order or cadaver sex. At C2-C5, the difference between preintubation baselines (second-first value) equaled −0.7 ± 2.5 degrees, which was not statistically significant.

Experiment 1: Primary Results. Cadaver laryngoscope force application and Oc-C5 extension at stages 2, 3, and 4 are summarized graphically in figure 3, with corresponding values from our patient intubation study[16] (additional laryngoscope force and segmental motion data from stages 2, 3, and 4 are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Experiment 1: tables 1, 2, and 3, respectively). In cadavers, maximum laryngoscope force and cervical spine motion occurred at stage 3 of intubation, which was also observed in patients.

Stage 3 intubation forces and cervical spine motion in cadavers and patients are summarized and compared in table 2 (complete linear mixed-effect models for each variable are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Experiment 1: table 4; all group–laryngoscope interaction terms were not significant). Laryngoscope forces did not differ between cadavers and patients. Extension at Oc-C2 did not differ between cadavers and patients. In contrast, C2-C5 extension in cadavers was less than that in patients (P = 0.001); modeled mean cadaver–patient difference was −6.4 degrees (95% CI, −10.1 to −2.8 degrees). Overall Oc-C5 extension was not significantly different in cadavers than in patients; modeled mean cadaver–patient difference was −5.9 degrees (95% CI, −11.9 to 0.20 degrees). The motion/force ratio did not differ between cadavers and patients, and the center of laryngoscope force application also did not differ.

Baseline values for C1-C2 extension in the intact state were obtained in experiment 1. There was no difference between cadavers and patients in C1-C2 extension:
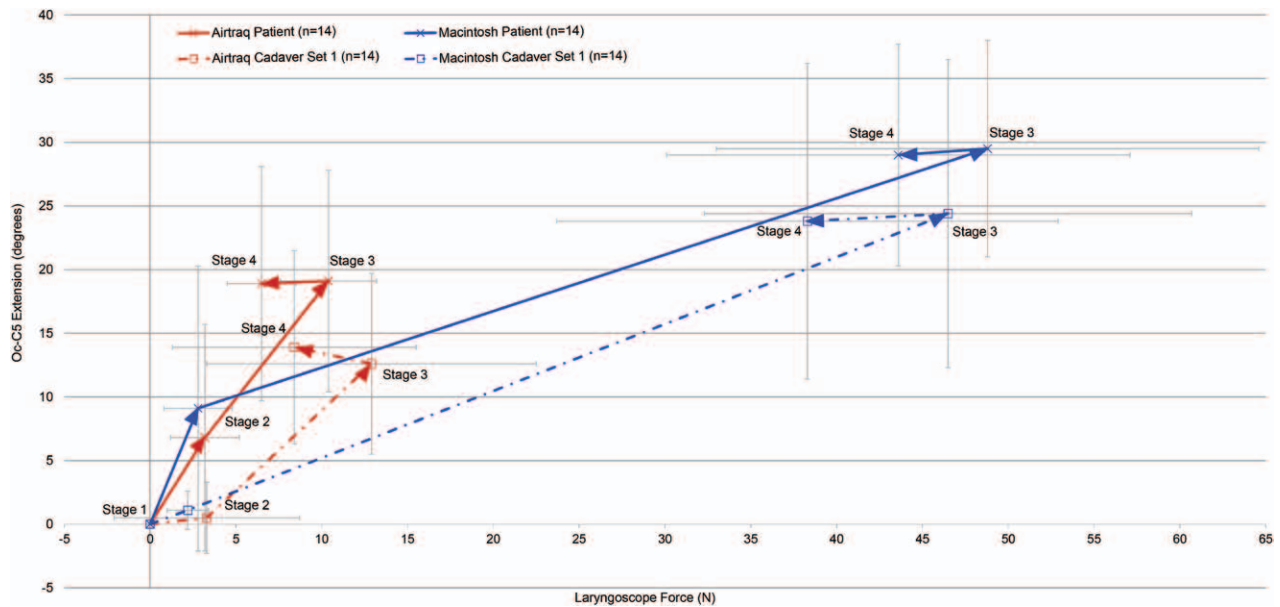
Fig. 3. Experiment 1. Laryngoscope force and overall (Oc-C5) cervical spine extension from Macintosh (*blue*) and Airtraq (*red*) laryngoscopes from patients[16] (*X, solid lines*) and cadaver set 1 (*squares, dot-dashed lines*) during the four stages of intubation: stage 1—preintubation baseline, defined as zero force and zero extension; stage 2—laryngoscope introduction; stage 3—laryngoscope placement (final); and stage 4—intubation. Values are shown as mean ± SD.

Table 2. Experiment 1: Laryngoscope Force Application and Cervical Spine Motion at Intubation Stage 3—Laryngoscope Placement (Final) in Cadavers and Patients

| Variables | Laryngoscope | Group | | Type 3 Test of Fixed Effect for Group (Cadaver vs. Patient), P Value |
		Cadavers, Intubation Set 1 (n = 14)	Patients (n = 14)*	
Total force, N	Macintosh	46.5 ± 14.2	48.8 ± 15.8	0.900
	Airtraq	12.9 ± 9.6	10.4 ± 2.8	
Oc-C5, degrees of extension	Macintosh	24.4 ± 12.1	29.5 ± 8.5	0.056
	Airtraq	12.6 ± 7.1	19.1 ± 8.7	
Cervical motion (Oc-C5) change per unit of force change between stages 2 and 3, degrees/N	Macintosh	0.6 ± 0.4	0.5 ± 0.2	0.630
	Airtraq	1.4 ± 2.1†	2.0 ± 1.4	
Center of force, mm from distal tip of laryngoscope	Macintosh	36 ± 6	35 ± 6	0.353
	Airtraq	40 ± 9	46 ± 13	
Oc-C2, degrees of extension	Macintosh	22.0 ± 10.0	19.6 ± 10.3	0.836
	Airtraq	13.8 ± 4.8	15.1 ± 7.4	
C2-C5, degrees of extension	Macintosh	2.4 ± 4.9	10.0 ± 6.8	0.001‡
	Airtraq	−1.2 ± 5.2	4.0 ± 5.6	

Values are expressed as mean ± SD.

* All patient data were previously reported by Hindman *et al.*[16] † Airtraq group value (n = 13) excludes an outlier value from one cadaver (−28.4 degrees/N), which was the result of 6.8 degrees of motion with a force change of −0.24 N. If the outlier value is included, Airtraq group value (n = 14) equals −0.7 ± 8.2 degrees/N. ‡ Significant at overall 5% false discovery rate for six comparisons.

Macintosh (cadavers: 6.9 ± 5.5 degrees; patients: 8.1 ± 4.7 degrees; $P = 0.3519$); Airtraq (cadavers: 4.8 ± 3.8 degrees; patients: 5.5 ± 4.8 degrees; $P = 0.1159$).

During experiment 1, marked airway tissue deformation was noted after intubation in some cadavers. Most obvious were instances in which the tongue was deformed after compression by the Macintosh laryngoscope blade creating a midline "channel" on the tongue (examples of postintubation tongue deformation are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Experiment 1: fig. 1).

As described in Materials and Methods, Experiment 2, an *ad hoc* decision was made to perform subsequent cadaver experiments in two subgroups that differed in the time allowed for potential tissue recovery: subgroup A (18 to 24 h recovery; n = 10) or subgroup B (1 h recovery; n = 4). Subgroups also differed in tissue temperature and state of C1-C2 stability (intact *vs.* injured).

Experiment 2: Effect of Repeated Intubations

Experiment 2: Control Measurements. In experiment 2, 8 of 10 subgroup A cadavers (head/neck temperature = 7.1° ± 1.9°C) underwent a second (intact C1-C2) and a third (injured C1-C2) set of intubations: seven cadavers had paired intubations (Macintosh and Airtraq) in both sets and one cadaver was intubated only with a Macintosh in both sets. Subgroup B cadavers (n = 4) underwent a second set of intubations (injured C1-C2).

Cervical spine position (Oc-C5) at the two preintubation baselines (set 2 *vs.* set 1, set 3 *vs.* set 2) did not differ with either laryngoscope (specific values for these control measurements are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Experiment 2, Control Measurements). Because preintubation baseline cervical spine positions were equivalent between successive intubation sets, laryngoscope forces and cervical spine motion could be compared among sets.

Experiment 2: Primary Results. Pooled cadaver laryngoscope force application and cervical motion at stages 2, 3, and 4 from intubation sets 1, 2, and 3 are summarized graphically in figure 4. Subgroup and pooled data for stage 3 laryngoscope force and Oc-C5 extension during intubation sets 1, 2, and 3 are summarized in table 3 (complete linear mixed-effect models for laryngoscope force and Oc-C5 extension are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Experiment 2, Primary Results: tables 5 and 6, respectively; in both models, the effect of subgroup was not significant and all interaction terms were not significant).

There was a difference over all intubation sets in total laryngoscope force ($P = 0.0015$). The effect of repeated intubations on force was almost entirely explained by differences between sets 1 and 2 ($P = 0.002$); modeled mean set 2/set 1 force ratio was 0.607 (95% CI, 0.455 to 0.810), without a force difference between sets 2 and 3. In contrast, there was not a difference over all intubation sets in Oc-C5 extension. However, for Oc-C5 extension, there was a difference between sets 1 and 2 ($P = 0.025$); modeled mean set 2–set 1 difference was –6.1 degrees (95% CI, –11.4 to –0.9), with no difference in Oc-C5 extension between sets 2 and 3.

Experiment 3: Motion of an Injured C1-C2 Segment

Experiment 3: Control Measurements. In experiment 3, C2 endplate length at the two preintubation baselines (intact C1-C2—stage 1 *vs.* injured C1-C2—stage 1) did not differ with either laryngoscope. C1-C2 intervertebral angle at the two preintubation baselines did not differ with either laryngoscope. C1-C2 canal space at the two preintubation baselines did not differ with either laryngoscope (specific values for these control measurements are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Experiment 3, Control Measurements). With an injured C1-C2 segment, intubations were performed in sequence 1 (first Macintosh and then Airtraq; n = 6) and sequence 2 (first Airtraq and then Macintosh; n = 5), with one cadaver intubated only with the Macintosh.

Experiment 3: Primary Results. Primary results for experiment 3 are summarized in table 4 (complete linear mixed-effect models for each variable are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Experiment 3: Primary Results: table 7; in all models, all subgroup interaction terms were not significant). Laryngoscope force did not differ between intubations with intact and injured C1-C2 segments although greater force was applied with
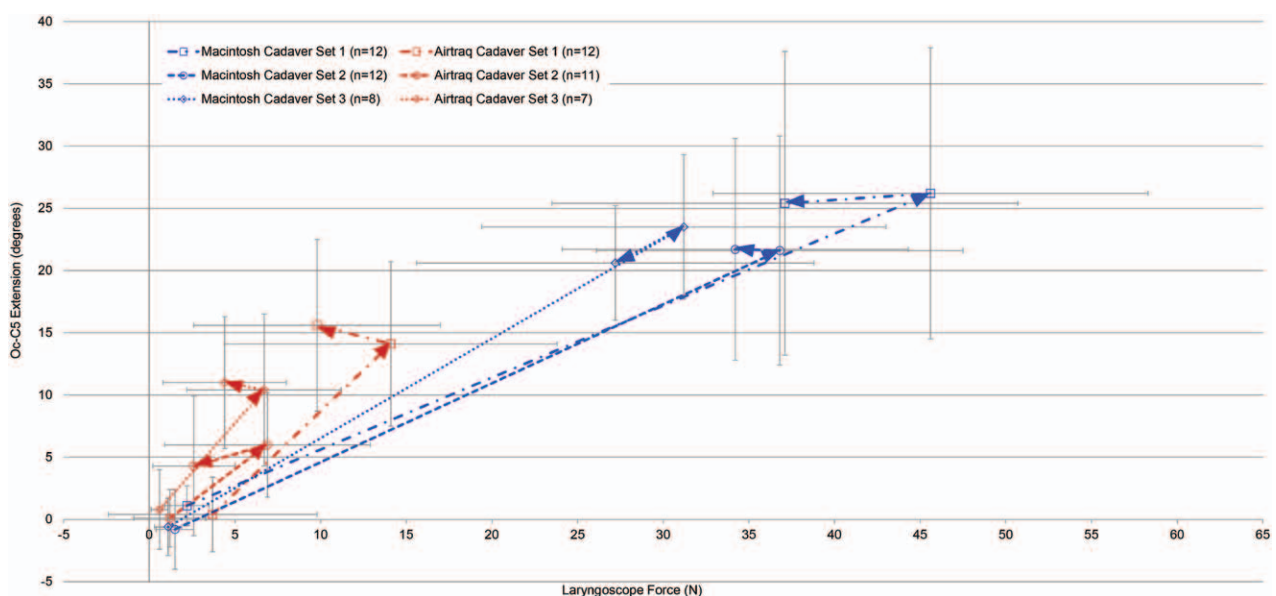
Fig. 4. Experiment 2. Cadaver laryngoscope force and overall (Oc-C5) cervical spine extension from Macintosh (*blue*) and Airtraq (*red*) laryngoscopes in intubation set 1 (*squares, dot-dash lines*), set 2 (*circles, dashed lines*), and set 3 (*diamond, dotted lines*). For figure clarity, intubation stages are not labeled but follow the same pattern as in figure 3. Values are shown as mean ± SD.

Table 3. Experiment 2: Effect of Repeated Intubations in Cadavers on Laryngoscope Force and Cervical Spine Motion at Stage 3—Laryngoscope Placement (Final)

Variables	Laryngoscope	Cadaver Subgroup	Intubation Set 1	Intubation Set 2	Intubation Set 3	Type 3 Test of Fixed Effect for Intubation Set, P Value	Set 1 vs. Set 2, Modeled P Value	Set 2 vs. Set 3, Modeled P Value
Total force, N	Macintosh	A	49.0 ± 13.4	33.7 ± 10.1	31.2 ± 11.8	0.0015*	0.002*	0.333
		B	38.9 ± 9.3	43.0 ± 10.5				
		Pooled	45.6 ± 12.7	36.8 ± 10.7				
	Airtraq	A	15.6 ± 9.2	8.0 ± 7.1	6.7 ± 4.5			
		B	11.2 ± 11.5	4.9 ± 3.1				
		Pooled	14.1 ± 9.7	6.9 ± 6.0				
Oc-C5, degrees of extension	Macintosh	A	28.5 ± 13.1	21.9 ± 11.3	23.5 ± 5.8	0.0751	0.025*	0.299
		B	21.7 ± 8.2	21.2 ± 3.5				
		Pooled	26.2 ± 11.7	21.6 ± 9.2				
	Airtraq	A	13.6 ± 5.5	6.0 ± 3.4	10.4 ± 6.1			
		B	14.9 ± 9.5	5.9 ± 5.8				
		Pooled	14.1 ± 6.6	6.0 ± 4.2				

Values are expressed as mean ± SD.
* Significant at 5% overall false discovery rate for six comparisons.

Table 4. Experiment 3, Primary Results: Cadaver Laryngoscope Force and C1-C2 motion at Stage 3—Laryngoscope Placement (Final), Intact and Injured C1-C2 Segment

Variables	Laryngoscope	C1-C2 Condition Intact	C1-C2 Condition Injured	Linear Mixed-effect Model, P Value*
Total force, N	Macintosh	35.4 ± 9.7	35.2 ± 12.3	
	Airtraq	9.2 ± 8.5	6.0 ± 4.0	
C1-C2, degrees of extension	Macintosh	4.7 ± 4.9	7.3 ± 4.2	Intact vs. injured: P = 0.816
	Airtraq	2.7 ± 4.6	2.3 ± 3.3	Injured, Macintosh vs. Airtraq: P = 0.028
Change in C1-C2 canal space, mm	Macintosh	−1.0 ± 1.1	−1.0 ± 1.4	Intact vs. injured: P = 0.278
	Airtraq	−0.6 ± 0.9	−1.2 ± 1.7	Injured, Macintosh vs. Airtraq: P = 0.376
C1-C2 canal space, mm	Macintosh	18.7 ± 1.4	18.0 ± 2.0	
	Airtraq	18.8 ± 1.6	17.6 ± 2.0	
C2 canal space, mm	Macintosh	15.9 ± 1.7	16.0 ± 1.5	
	Airtraq	15.9 ± 1.6	16.2 ± 1.5	

Values are expressed as mean ± SD.
* None of the P values are significant at overall 5% false discovery rate for four comparisons.

the Macintosh (approximately 35 N) than with the Airtraq (approximately 6 to 9 N). As expected, values for C2 canal space were equivalent between laryngoscopes and did not differ between intact and injured states.

C1-C2 Extension. There was no difference between the intact and injured state in C1-C2 extension ($P = 0.816$). During intubations when C1-C2 was injured, C1-C2 extension with the Macintosh did not differ from extension with the Airtraq ($P = 0.028$; significance threshold ≤ 0.0125; modeled mean Macintosh–Airtraq difference = 5.1 degrees (95% CI, 0.1 to 10.4).

Change in C1-C2 Canal Space. There was no difference between the intact and injured state in C1-C2 canal change ($P = 0.278$). When C1-C2 was injured, the change in C1-C2 canal space (subluxation) did not differ between the Macintosh and Airtraq ($P = 0.376$).

C1-C2 Canal Space. C1-C2 canal space (approximately 18 mm) did not differ between intubations with intact and injured C1-C2 segments. During intubations with an intact C1-C2 segment, individual values for C1-C2 canal space were greater than or equal to corresponding values for C2 canal space in all cases.

During intubations with an injured C1-C2 segment, individual values for C1-C2 canal space were less than the corresponding values for C2 canal space in 2 of 12 Macintosh intubations (13.5, 17.3 mm [0.1, 0.4 mm less than corresponding values for C2 canal space, respectively]) and 0 of 11 Airtraq intubations (minimum value = 13.7 mm [0.2 mm

greater than corresponding values for C2 canal space]). During intubations with an injured C1-C2 segment, C1-C2 canal space exceeded 8 mm (minimum sagittal spinal cord diameter) in all cases.

Experiment 3: "Force-corrected" Results. In Primary Results, Macintosh force applied during intubations with an injured C1-C2 segment (35.2 ± 12.3 N) was 10.5 ± 13.9 N (19 ± 32%) less than the clinically comparable Macintosh force applied during corresponding set 1 intubations (45.6 ± 12.7 N; n = 12; P = 0.0342). Likewise, with the Airtraq, force applied during intubations with an injured C1-C2 segment (6.0 ± 4.0 N) was 8.3 ± 7.9 N (52 ± 27%) less than the clinically comparable Airtraq force applied during corresponding set 1 intubations (14.3 ± 10.2 N; n = 11; P = 0.0010). Because primary observations of the motion of injured C1-C2 segments took place with laryngoscope forces that were less than clinically comparable values, we speculated that the observed motions of injured C1-C2 segments (table 4) might be less than what would occur with clinically normal forces. Accordingly, as described in Materials and Methods, Experiment 3, we calculated *post hoc* "force-corrected" values of C1-C2 motion to estimate motion of injured C1-C2 segments that would occur during intubations with clinically normal forces.

"Force-corrected" results for experiment 3 are summarized in table 5 (complete linear mixed-effect models for each "force-corrected" variable are provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; experiment 3, "Force-corrected" Results: table 8).

C1-C2 Extension. With "force-correction," there was no difference between the intact and injured state in C1-C2 extension (P = 0.951). During intubations when C1-C2 was injured, C1-C2 extension was not greater with the Macintosh than with the Airtraq (P = 0.144); modeled mean Macintosh–Airtraq difference = 4.8 degrees (95% CI, –3.1 to 12.7).

Change in C1-C2 Canal Space. With "force-correction," change in C1-C2 canal space (subluxation) during

intubations in the injured state did not differ from the intact state (P = 0.028; significance threshold ≤0.025). During intubations when C1-C2 was injured, the change in C1-C2 canal space was significantly less with the Macintosh than with the Airtraq (P = 0.004); modeled mean Macintosh–Airtraq difference = 2.8 mm (95% CI, 0.7 to 4.9).

C1-C2 Canal Space. During intubations when C1-C2 was injured, with the Macintosh, individual values for "force-corrected" C1-C2 canal space were less than corresponding values for C2 canal space in 1 of 12 intubations (17.1 mm [0.5 mm less than values for C2 canal space]). When C1-C2 was injured, with the Airtraq, individual values for "force-corrected" C1-C2 canal space were less than the corresponding C2 canal space in 7 of 11 intubations (8.6, 8.7, 13.9, and 15.9 mm [7.1, 5.9, 2.6, and 0.8 mm less than values for C2 canal space, respectively]) but exceeded 8 mm (minimum sagittal spinal cord diameter) in all cases.

Discussion

Experiment 1: Primary Intubation Biomechanics

With limitations, cadavers may serve as clinically applicable models of cervical spine biomechanics during endotracheal intubation. Using two different laryngoscopes, we observed that intubation conditions, total laryngoscope force, and overall (Oc-C5) cervical spine extension were indistinguishable between cadavers and patients. Our findings are compatible with those reported by Lennarson *et al.*,[10] in which Oc-C5 extension with Macintosh intubation was not significantly different between cadavers and patients (medians of 16.9 degrees *vs.* 20.3 degrees, respectively).

A limitation of experiment 1 is that cadaver and patient groups each consisted of a small number of subjects (n = 14). Irrespective of identifiable differences between cadavers and patients, these small groups may not be sufficiently large to be representative of the general population. Consequently, our comparisons of cadaver and patient cervical spine

Table 5. Experiment 3, "Force-corrected" Results: Cadaver Laryngoscope Force and C1-C2 Motion at Stage 3—Laryngoscope Placement (Final), Intact (Set 1) and Injured C1-C2 Segment

Variables	Laryngoscope	C1-C2 Condition		Linear Mixed-effect Model, P Value
		Intubation Set 1 Intact	"Force-corrected" Injured	
Total force, N	Macintosh	45.6 ± 12.7	45.6 ± 12.7	
	Airtraq	14.3 ± 10.2	14.3 ± 10.2	
C1-C2, degrees of extension	Macintosh	7.6 ± 5.5	9.9 ± 6.3	Intact *vs.* injured: P = 0.951
	Airtraq	5.0 ± 4.3	4.2 ± 7.8	Injured, Macintosh *vs.* Airtraq: P = 0.144
Change in C1-C2 canal space, mm	Macintosh	–0.9 ± 0.8	–1.1 ± 1.7	Intact *vs.* injured: P = 0.028
	Airtraq	–0.9 ± 0.9	–3.1 ± 4.5	Injured, Macintosh *vs.* Airtraq: P = 0.004*
C1-C2 canal space, mm	Macintosh	19.6 ± 2.4	17.9 ± 1.7	
	Airtraq	19.6 ± 2.1	15.7 ± 4.0	

Values are expressed as mean ± SD.
* Significant at overall 5% false discovery rate for four comparisons.

biomechanics are subject to both type I (false positive) and type II (false negative) errors. Because cadaver studies were performed less than 1 month after completion of patient studies, and because all intubation protocols, personnel, and data acquisition equipment were identical in both groups, differences between cadavers and patients in cervical spine biomechanics are probably not due to methodological differences.

One of the many identifiable differences between cadavers and patients was age. Many prior cadaver intubation studies do not report cadaver age,[5–9] but, of those that do, advanced age is the rule (mean age, 75 to 87 yr).[10–15] With increasing age, there are progressive increases in the prevalence and severity of cervical spondylosis[41] and corresponding decreases in range of motion,[42,43] particularly in subaxial segments. Therefore, our observation of less C2-C5 extension in elderly cadavers is not surprising and identifies an important potential limitation of cadaver intubation models. Specifically, motion of any given cadaver cervical segment cannot be automatically assumed to be the same as that of patients. In our study, we observed that intact (stable) C1-C2 extension during intubations in cadaver subjects was indistinguishable from C1-C2 extension observed in patients. This suggests that the biomechanical characteristics of the segment of interest (C1-C2) in our cadaver subjects were comparable with those of patients, and, hence, our results regarding C1-C2 motion in the injured state may be clinically applicable.

Another identifiable difference between cadavers and patients was tissue temperature. All cadaver intubation studies state (or suggest) that cadavers were studied at "room temperature," but *none* report tissue temperature. Because, in our study, primary intubation biomechanics appear to be indistinguishable between cadavers and patients, tissue temperatures between 20° to 37°C may not have large effects on tissue biomechanical properties. This is consistent with *in vitro* studies that have reported, with some exceptions, that tissue relaxation parameters are not highly temperature dependent.[44,45]

Experiment 2: Effect of Repeated Intubations

During *in vitro* biomechanical testing of nonliving tissue, the relation between applied forces and tissue deformation/motion undergoes sequential changes during the first few load cycles; this process is referred to as preconditioning.[19,20] Accordingly, in virtually all *in vitro* studies of segmental spinal motion, force/motion characteristics are determined only after at least two load cycles.[20,21,46,47] We had anticipated that, because of *in vitro* tissue preconditioning, cadaver intubation biomechanics might change with repeated intubations. However, the effect was greater than anticipated, as evidenced by marked deformation of cadaver airway tissue (tongue) after high-force Macintosh intubations. As described in Materials and Methods, we made several *ad hoc* changes in experimental design in an attempt to

compensate. We had hoped that, with a long postintubation tissue recovery period, airway morphology and intubation biomechanics might return to original (set 1) conditions. Because this was not preplanned, subgroup assignment was not randomized but was instead determined by cadaver, laboratory space, and investigator availability. These *ad hoc* changes in experimental design resulted in two subgroups (A and B) that differed in tissue recovery period, temperature, number of intubations, and condition of the C1-C2 segment (intact *vs.* injured). Rather than reversing tissue changes, and/or clarifying the factors that affect cadaver intubation biomechanics, our changes in experimental design increased analytic complexity. To partially adjust for these potential confounders, we included subgroup as a variable in our linear mixed-effect models. Although subgroup was not a significant factor, we cannot exclude the possibility (or quantify the effect) of these individual factors on our results.

In experiment 2, cadaver intubation force and Oc-C5 extension changed (decreased) with repeated intubations. The effect of repeated intubations was apparent between set 1 and set 2, with no discernable change thereafter. This is consistent with *in vitro* preconditioning effects. Therefore, we suggest that prior cadaver intubation studies that have used repeated intubations (4 to 6 intubations,[9,10,12,15] 9 to 16 intubations,[11,13] or 52 intubations[14]), but that have not controlled for serial changes in laryngoscope force and/or cervical spine motion, may not accurately predict cervical spine motion.

Experiment 3: Motion of an Injured C1-C2 Segment

In experiment 3, we surgically created a type II odontoid fracture, which is the most common form of traumatic C2 injury in adults[35,48,49] and which is generally considered to be clinically "unstable."[50–52]

Using the primary (*non*force-corrected) data, our hypotheses regarding C1-C2 motion were not supported. First, C1-C2 motion during intubation (both extension and change in C1-C2 canal space) was not significantly greater in the presence of a type II odontoid fracture than when C1-C2 was intact (stable). Second, in the presence of a type II odontoid fracture, C1-C2 motion did not significantly differ between a high-force (Macintosh) and a low-force (Airtraq) laryngoscope. However, because we noted that intubation forces with both laryngoscopes were less than clinically normal values (the effect of repeated intubations), we wondered if the observed motions underestimated the motion that would occur with clinically normal laryngoscope forces. Had we not measured intubation forces, we would not have known to consider such a possibility.

Accordingly, we compared C1-C2 motion between intact (stable) values obtained during set 1 intubations (force and motion values comparable with those of patients) with motion values of the injured C1-C2 segment that were "force-corrected." With "force-corrected" results, there was no difference between intact and injured states in C1-C2

extension, and, in the injured state, no difference between laryngoscopes in C1-C2 extension. *These are exactly the same conclusions as when primary (nonforce-corrected) data were used.* In contrast, using "force-corrected" data, in the presence of a type II odontoid fracture, there was *greater* change in C1-C2 canal space (subluxation) with the *low*-force (Airtraq) laryngoscope than with the *high*-force (Macintosh) laryngoscope. This is a paradoxical finding and may simply be a mathematical artifact of "force-correction." However, if it is not, then this finding adds to several key principles regarding cervical spine motion during intubation in the presence of an injured cervical segment.

Principles of Intubation Biomechanics with Injured Cervical Segments

The first principle is that the apparent "stability" of an injured cervical segment may differ among different modes of motion. Specifically, an injured segment may exhibit abnormal motion in one mode (*e.g.*, subluxation) but not in another (*e.g.*, extension). This concept is already well established in the spine biomechanics literature.[21] Therefore, to refer to a cervical segment as being "unstable" is an over-simplification—"stability" depends on the mode of motion being considered.

Second, although a segment may be injured, the remaining intact supportive structures (*e.g.*, ligaments, facets, *etc.*) may be sufficient to limit range of motion to values that are close to clinically normal values.[53] Thus, not all injured cervical segments are necessarily "unstable" with regard to endotracheal intubation. Similarly, "stability" of a cervical segment is not binary (100% stable *vs.* 100% unstable) but, instead, exists on a continuum determined by the net integrity of the numerous elements (bone, ligament, muscle, *etc.*) that contribute to the gestalt stiffness (motion/force) behavior of the segment.

Third, during intubation, motion of a cervical segment will depend on the force "seen" at the *spinal level*. Forces at the cervical spinal level are almost certainly *not* the same as the contact force of the laryngoscope. For example, in our prior clinical study, at equivalent laryngoscope contact forces (10 N), cervical extension with the Macintosh was approximately 50% *less* than that with the Airtraq.[16] With the Macintosh, much of the applied force appears to be going toward processes other than cervical spine motion—almost certainly airway tissue deformation/displacement. Thus, measuring force applied by the laryngoscope to airway tissue does not completely explain the motion of the cervical spine.

Fourth, during intubation, motion of a cervical segment is likely determined both by the magnitude of force and by its direction—the force vector. For example, when force is applied perpendicular (at 90 degrees) to a plane of instability, there is no motion in the plane of instability. Thus, our "force-corrected" data suggest that the force vector of the Airtraq may be more closely aligned with the anterior-posterior plane of C1-C2 than the force vector of the Macintosh.

In our experiment, when C1-C2 was injured, 3.1 ± 4.5 mm of C1-C2 subluxation occurred with 14.3 ± 10.2 N of Airtraq force ("force-corrected" values). This amount of subluxation is consistent with findings in an *in vitro* isolated Oc-C2 model wherein, in the presence of a type II odontoid fracture, 10 N of force applied directly anteriorly to C2 resulted in 3.0 ± 0.9 mm of subluxation relative to C1.[47] Therefore, our "force-corrected" data agrees quantitatively with *direct* observations made by other investigators and supports the concept that the force *vector* (not just force *magnitude*) may be the key in determining the motion of an unstable cervical segment.

Clinical Airway Management Implications

Although often referred to as "unstable," a type II odontoid fracture results in relatively small increases in C1-C2 motion during endotracheal intubation. In our study, the *maximum* ("force-corrected") value of C1-C2 extension with the Macintosh with a type II odontoid fracture (9.9 ± 6.3 degrees) is indistinguishable from *stable* C1-C2 extension during Macintosh intubations in anesthetized patients (8.1 ± 4.7 degrees)[16] or maximal voluntary *stable* C1-C2 extension (from neutral to protrusion position) in awake patients 8.3 ± 5.8 degrees.[54] When compared with the Macintosh, with the Airtraq, it appears that C1-C2 extension with a type II odontoid fracture may be marginally (but not statistically significantly) less (approximately 5 degrees less, both without and with "force-correction"). However, because maximum Macintosh extension is so close to physiologically normal values, marginally less extension with the Airtraq cannot be considered to be necessarily "safer." Although our findings differ quantitatively from two other recent cadaver studies,[14,15] we agree with both that, in the presence of a type II odontoid fracture, there is not a significant difference between the Macintosh and the Airtraq in C1-C2 extension.

With regard to C1-C2 canal change (subluxation) in the presence of a type II odontoid fracture, intubation with the Macintosh resulted in very little motion (approximately 1 mm, both without and with "force-correction"), and in no case was subluxation sufficient to result in direct cord compression. In our study, change in C1-C2 canal space with Macintosh intubation (-1.0 ± 1.4 mm) was indistinguishable from that reported by Donaldson *et al.*[8] in a similar cadaver model of C1-C2 instability (-1.2 ± 0.5 mm) and is also indistinguishable from intervertebral subluxation observed during maximal voluntary extension in awake patients with stable cervical spines (approximately 1 mm).[55,56] Thus, with a type II odontoid fracture, Macintosh intubation does not appear to place the cord at risk of compression. Paradoxically, with the Airtraq, despite lesser total force than the Macintosh, our "force-corrected" (maximal value) data indicated that there was a greater C1-C2 subluxation, which, in some (2 of 11) instances, was nearly sufficient to result in direct cord compression. Thus, in the presence of a type II odontoid fracture, use of the Macintosh might be preferred

over the Airtraq. However, *overall*, use of *either* laryngoscope to intubate patients with a type II odontoid fracture would seem reasonable and to *not* carry a substantive risk of cervical spinal cord injury, so long as other ligamentous structures at C1-C2 are intact.

Limitations

We observed and discussed why, because of *in vitro* preconditioning effects, intubation forces and cervical spine motion changed with repeated intubations in cadavers. We attempted to correct for these effects but acknowledge that our method of "force-correction" may not have been correct. We assumed a linear relation between force and motion in the injured C1-C2 segment. If the relation is *non*linear over the range of forces studied, our "force-correction" method would tend to *over*estimate C1-C2 motion (additional discussion regarding our method of "force correction" is provided in Supplemental Digital Content 1, http://links.lww.com/ALN/B193; Discussion, Limitations).

An additional limitation is that cervical spine image analysis and glottic view analysis were performed by single investigators who were not blinded to type of laryngoscope. Accordingly, investigator bias in these outcome measures cannot be excluded.

Finally, some patients with cervical spine injury may require intubation in the presence of preexisting bony displacement and/or congenital canal stenosis, hematoma, disc herniation, *etc.*[57] In the absence of prior injury, brief periods (seconds-minutes) of moderate cord compression are relatively well tolerated,[58,59] whereas, with preexisting cord injury/compression, the amount and duration of "tolerable" compression is likely to be much less.[60] Consequently, our general conclusion regarding the clinical utility/safety of either the Macintosh or Airtraq in the setting of a type II odontoid fracture may not apply in the setting of preexisting bony displacement and/or cervical cord injury.

Conclusion

With limitations, cadavers may be clinically applicable models of intubation biomechanics and cervical spine motion. Repeated intubations change cadaver tissue properties, and these changes should be accounted for in future studies using cadaver models of cervical spine motion. In the setting of a type II odontoid fracture, C1-C2 motion during intubation with either the Macintosh or the Airtraq does not appear to greatly exceed physiologic values or to have a high likelihood of hyperextension or direct cord compression. Our study shows that the relation between laryngoscope force and motion of an injured cervical segment is complex and is not readily predicted at our current level of knowledge.

Acknowledgments

Competing Interests

Correspondence

Address correspondence to Dr. Hindman: Department of Anesthesia—6JCP, University of Iowa Hospitals and Clinics, 200 Hawkins Drive, Iowa City, Iowa 52242. brad-hindman@uiowa.edu. Information on purchasing reprints may be found at www.anesthesiology.org or on the masthead page at the beginning of this issue. ANESTHESIOLOGY's articles are made freely accessible to all readers, for personal use only, 6 months from the cover date of the issue.

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