Supplemental Digital Content 1

RESULTS

Experiment 1: Primary Intubation Biomechanics

In Experiment 1, cadavers were intubated twice (intubation Set 1) in random order: sequence 1 (Macintosh then Airtraq [n=7]: female=3, male=4) and sequence 2 (Airtraq then Macintosh [n=7]: female=6, male=1). It was a coincidence that the sex imbalance in intubation sequence in cadavers was the same as in our prior patient study.[1] As summarized in Table 1, in cadavers at stage 2 (laryngoscope introduction), force application with the Macintosh and Airtraq were equivalent (2-3 N), and laryngoscope forces were equivalent to those observed in patients.[1] In cadavers at stage 2, extension at each intervertebral segment (or combination of segments Oc-C2, C2-C5, Oc-C5) did not significantly differ between the Macintosh and Airtraq.

Table 1. Experiment 1: Cadaver Laryngoscope Force Application and Cervical Motion at Stage 2—Laryngoscope Introduction. Intubation Set 1 (intubations #1, #2)

Variable	Macintosh (n=14)	Airtraq (n=14)	*P* Value
Total force, N	2.2 ± 1.2	3.3 ± 5.4	0.7148
Intervertebral segment, degrees of extension			
Oc-C1	1.5 ± 1.8	0.2 ± 2.1	0.1189
C1-C2	-0.3 ± 2.9	0.4 ± 2.4	0.3575
C2-C3	0.1 ± 2.3	-0.8 ± 1.9	0.1937
C3-C4	0.3 ± 2.5	0.1 ± 2.1	0.8552
C4-C5	-0.5 ± 2.0	0.5 ± 2.2	0.1909
Combined Oc-C2	1.2 ± 2.2	0.7 ± 1.9	0.2676
Combined C2-C5	-0.1 ± 2.2	-0.2 ± 2.4	1.0000
Combined Oc-C5	1.1 ± 1.5	0.5 ± 2.8	0.5830
Cervical motion (Oc-C5) change per unit of force change between stages 1 and 2, degrees/N	0.6 ± 0.9	0.1 ± 2.4*	0.7869*

Values are expressed as mean ± SD.

* Airtraq group value excludes an outlier value from one cadaver (-9.5 degrees/N) which was the result of -1.4 degrees of motion with a force change of 0.15 N of force. *P* value is based on paired data from 13 cadavers. If the outlier value is included, Airtraq group value equals -0.6±3.4 degree/N and *P*=0.5016.

However, in cadavers at stage 2, Oc-C5 extension was less in than in patients[1]: Macintosh (1.1±1.5 *vs*. 9.1±11.2 degrees, respectively; *P*=0.0350); Airtraq (0.5±2.8 *vs.*

6.8±8.9 degrees, respectively; *P*=0.0602). Accordingly, in cadavers at stage 2, the amount of Oc-C5 motion that occurred per unit force application (degrees/N) was approximately 6-to-30-fold less than observed in patients[1]: (Macintosh: 0.6±0.9 *vs.* 3.6±4.9 degrees/N, respectively; Airtraq: 0.1±2.4 *vs.* 2.8±4.5 degrees/N, respectively). This indicates cadavers were significantly "stiffer" in the lower ranges of force and motion than were patients.

As summarized in table 2, in cadavers at stage 3 (laryngoscope placement, final), intubation forces and multi-segmental intervertebral motions differed between laryngoscopes. Specifically, there was nearly 4-fold greater force applied with the Macintosh than with the Airtraq (46.5±14.2 *vs*. 12.9±9.6 N, respectively; *P*=0.0001). The Macintosh-Airtraq difference in applied force did not differ as a function of either intubation sequence (*P*=0.3176), or cadaver sex (*P*=0.6064). The center of force application was not significantly more distal along the laryngoscope blade with the Macintosh than with the Airtraq (36±6 *vs*. 40±9 mm from the distal tip, respectively; *P*=0.1353). In cadavers at stage 3, extension at each intervertebral segment did not differ between the Macintosh and Airtraq except at Oc-C1 (15.2±6.0 *vs*. 9.0±3.8 degrees respectively; *P*=0.0031) and C3-C4 (2.1±3.3 *vs*. -0.7±2.8 degrees respectively; *P*=0.0245). When intervertebral segments were mathematically combined, at Oc-C2 there was greater extension with the Macintosh than with the Airtraq (22.0±10.0 *vs*. 13.8±4.8 degrees respectively; *P*=0.0052). Likewise, at C2-C5, there was greater extension with the Macintosh than the Airtraq (2.4±4.9 *vs.* -1.2±5.2 degrees, respectively; *P*=0.0245). In cadavers, overall (Oc-C5) cervical extension was greater with the Macintosh than with the Airtraq (24.4±12.1 *vs*. 12.6±7.1 degrees, respectively; *P*=0.0023). Macintosh-Airtraq differences in Oc-C5 extension did not differ as a function of cadaver sex (*P*=0.7972) but had a borderline association with intubation sequence (*P*=0.0530). Specifically, the Macintosh-Airtraq difference in Oc-C5 extension was numerically greater when the intubation sequence started with the Macintosh (sequence 1) than when starting with the Airtraq (sequence 2) (difference =17.5±9.4 *vs*. 6.0±8.2 degrees, respectively; *P*=0.0530). Finally, in cadavers, between stages 2 and 3 the amount of Oc-C5 motion (degrees) that occurred per unit force (N) applied by the laryngoscope differed between the Macintosh and Airtraq (0.6±0.4 *vs.* 1.4±2.1 degrees/N, respectively; *P*=0.0398). Macintosh-Airtraq differences in motion/force ratio did not differ as a function of intubation sequence (*P*=0.9452) or cadaver sex (*P*=0.8329).

Table 2. Experiment 1: Cadaver Laryngoscope Force Application and Cervical Motion at Stage 3—Laryngoscope Placement (final). Intubation Set 1 (intubations #1, #2)

Variable	Macintosh (n=14)	Airtraq (n=14)	*P* Value
Total force, N	46.5 ± 14.2	12.9 ± 9.6	0.0001

Center of force, mm from distal tip of laryngoscope	36 ± 6	40 ± 9	0.1353
Intervertebral segment, degrees of extension			
Oc-C1	15.2 ± 6.0	9.0 ± 3.8	0.0031
C1-C2	6.9 ± 5.5	4.8 ± 3.8	0.2676
C2-C3	1.5 ± 2.5	0.3 ± 1.4	0.1726
C3-C4	2.1 ± 3.3	-0.7 ± 2.8	0.0245
C4-C5	-1.2 ± 3.0	-0.9 ± 4.6	0.7354
Combined Oc-C2	22.0 ± 10.0	13.8 ± 4.8	0.0052
Combined C2-C5	2.4 ± 4.9	-1.2 ± 5.2	0.0245
Combined Oc-C5	24.4 ± 12.1	12.6 ± 7.1	0.0023
Cervical motion (Oc-C5) change per unit of force change between stages 2 and 3, degrees/N	0.6 ± 0.4	1.4 ± 2.1*	0.0398*

Values are expressed as mean ± SD.

* Airtraq group value 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. *P* value is based on paired data from 13 cadavers. If the outlier value is included, Airtraq group value equals -0.7±8.2 degree/N and *P*=0.1726.

In cadavers, between stage 3 (laryngoscope placement, final) and stage 4 (intubation), laryngoscope force application decreased with both the Macintosh (-8.2±8.1 N, *P*=0.0002; proportional change= -17±15%) and the Airtraq (-4.6±6.8 N, *P*=0.0203; proportional change= -29±57%). Nevertheless, as summarized in table 3, at stage 4 intubation force continued to significantly differ between Macintosh and Airtraq (*P*=0.0001). In contrast, between stages 3 and 4, Oc-C5 extension did not change either laryngoscope: Macintosh (-0.6±3.2 degrees, *P*=0.4631); Airtraq (1.3±3.3 degrees, *P*=0.1040). Between stages 3 and 4, the amount of Oc-C5 motion that occurred per unit force did not differ between the Macintosh and Airtraq, 0.2±0.6 *vs.* -0.1±1.1 degrees/N, respectively; *P*=0.6355. At stage 4, applied forces with both laryngoscopes were equivalent between cadavers and patients. [1] In cadavers and patients, the same general patterns and magnitudes of laryngoscope force reduction between stages 3 and 4, but with minimal concomitant changes in Oc-C5 extension, were observed.

Table 3. Experiment 1: Cadaver Laryngoscope Force Application and Cervical Motion at Stage 4—Intubation. Intubation Set 1 (intubations #1, #2)

Variable	Macintosh (n=14)	Airtraq (n=14)	*P* Value
Total force, N	38.3 ± 14.6	8.4 ± 7.1	0.0001
Intervertebral segment, degrees of extension			

Oc-C1	15.4 ± 6.8	9.8 ± 3.7	0.0245
C1-C2	7.2 ± 5.7	4.7 ± 4.5	0.0906
C2-C3	0.8 ± 2.2	0.0 ± 2.5	0.5416
C3-C4	1.0 ± 3.7	-0.6 ± 4.5	0.3258
C4-C5	-0.6 ± 4.5	-0.1 ± 5.0	0.6355
Combined Oc-C2	22.6 ± 10.9	14.5 ± 4.5	0.0203
Combined C2-C5	1.2 ± 5.0	-0.7 ± 5.0	0.2958
Combined Oc-C5	23.8 ± 12.4	13.9 ± 7.6	0.0052
Cervical motion (Oc-C5) change per unit of force change between stages 3 and 4, degrees/N	0.2 ± 0.6*	-0.1 ± 1.1	0.6355*

Values are expressed as mean ± SD.

* Macintosh group value excludes an outlier value from one cadaver (11.2 degrees/N) which was the result of 2.8 degrees of motion with a force change of 0.25 N of force. *P* value is based on paired data from 13 cadavers. If the outlier value is included, Macintosh group value equals 1.0±3.0 degree/N and *P*=0.3910.

In Experiment 1, cadavers and patients were compared in terms of intubation biomechanics. Complete linear mixed effect models for intubation forces and cervical spine motion in cadavers and patients are summarized in table 4.

Table 4. Experiment 1: Linear Mixed Effect Models to Compare Cadaver (Intubation Set 1) and Patient Intubation Biomechanics

Variable	Type 3 Tests of Fixed Effects			Comparisons between Groups			
	Effect	F Value	*P* value	Laryngoscope	Cadaver Mean (SE)	Patient Mean (SE)	Bonferroni adjusted *P* value
Total Force, N	Group (Cadavers, Patients)	0.02	0.900	Airtraq	10.02 (2.12)	10.04 (0.82)	>0.99*
	Laryngoscope (Macintosh, Airtraq)	23.54	<.0001	Macintosh	44.47 (3.70)	46.20 (4.39)	>0.99*
	Group*Laryngoscope Interaction	0.04	0.853	Overall	Ratio (cadaver/patient): 0.98 (95% CI: 0.71, 1.36)		0.900†
Oc-C5 extension, degrees	Group (Cadavers, Patients)	4.00	0.056	Airtraq	12.59 (2.48)	19.14 (2.48)	0.138*
	Laryngoscope (Macintosh, Airtraq)	32.48	<.0001	Macintosh	24.39 (2.48)	29.54 (2.48)	0.299*
	Group*Laryngoscope Interaction	0.13	0.723	Overall	Difference (cadaver-patient): -5.85 (95% CI: -11.87, 0.16)		0.056†
Oc-C5 Motion/Force ratio, degrees/N	Group (Cadavers, Patients)	0.24	0.630	Airtraq	1.56 (0.50)	2.04 (0.48)	0.985*
	Laryngoscope (Macintosh, Airtraq)	16.53	0.0004	Macintosh	0.58 (0.08)	0.48 (0.08)	0.754*
	Group*Laryngoscope Interaction	0.88	0.357	Overall	Difference (cadaver-patient): -0.19 (95% CI: -0.98, 0.61)		0.630†
Oc-C2 extension, degrees	Group (Cadavers, Patients)	0.04	0.836	Airtraq	13.82 (1.66)	15.13 (1.66)	>0.99*
	Laryngoscope (Macintosh, Airtraq)	16.91	0.0003	Macintosh	22.02 (0.07)	19.55 (2.71)	>0.99*
	Group*Laryngoscope Interaction	1.51	0.230	Overall	Difference (cadaver-patient): 0.58 (95% CI: -5.15, 6.31)		0.836†
C2-C5	Group	13.17	0.001	Airtraq	-1.23 (1.51)	4.01 (1.51)	0.036*

extension, degrees	(Cadavers, Patients)						
	Laryngoscope (Macintosh, Airtraq)	15.96	0.0005	Macintosh	2.37 (1.51)	9.99 (1.51)	0.002*
	Group*Laryngoscope Interaction	0.98	0.331	Overall	Difference (cadaver-patient): -6.43 (95% CI: -10.08, -2.79)		0.001†
Center of force, mm	Group (Cadavers, Patients)	0.89	0.353	Airtraq	40.14 (2.94)	45.83 (2.94)	0.367*
	Laryngoscope (Macintosh, Airtraq)	12.46	0.002	Macintosh	36.06 (1.65)	35.44 (1.65)	>0.99*
	Group*Laryngoscope Interaction	2.36	0.136	Overall	Difference (cadaver-patient): -2.53 (95% CI: -8.05, 2.98)		0.353†

Natural log (ln) transformation was utilized to normalize the force data distribution, with transformed data used in the analysis. Mean estimates were computed from the ln means by back-transformation, and corresponding standard error (SE) calculated by the delta method.

Patient data derived from original source data from Hindman *et al*.[1]

* For Bonferroni correction, reported *P* value is multiplied x 2 original (unadjusted) value.

† Single comparison; reported *P* value is not adjusted.

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; two examples are shown in figure 1.

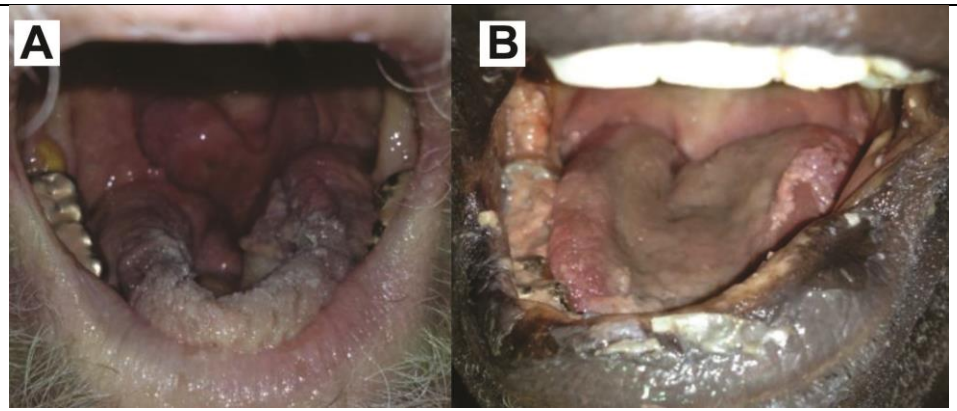

Fig. 1. Experiment 1. Tongue deformation after Macintosh intubations in two subgroup A cadavers, panels A and B.

Experiment 2: Effect of Repeated Intubations

Experiment 2, Control Measurements

Cervical spine position at the two preintubation baselines (Set 2—stage 1 and Set 1—stage 1) did not differ with either laryngoscope Specifically, for the Macintosh (n=12), the difference between Set 2 and Set 1 intubations (Set 2 minus Set 1 difference) at preintubation baseline (stage 1) Oc-C5 position equaled -0.8±7.7 degrees; *P*=0.3013. For the Airtraq (n=11), the difference between intubation sets (Set 2 minus Set 1 difference) at preintubation baseline Oc-C5 position equaled 3.5±8.5 degrees; *P*=0.2402.

Similarly, cervical spine position at the two preintubation baselines (Set 3—stage 1 and Set 2—stage 1) did not differ with either laryngoscope. Specifically, for the Macintosh (n=8), the difference between Set 3 and Set 2 intubations (Set 3 minus Set 2 difference) at preintubation baseline Oc-C5 position equaled 0.7±8.9 degrees; *P*=0.9453. For the Airtraq (n=7), the difference between intubation sets (Set 3 minus Set 2 difference) at preintubation baseline Oc-C5 position equaled -3.3±5.5 degrees; *P*=0.1563.

Experiment 2, Primary Results

The complete linear mixed effect model for the effect of repeated intubation on laryngoscope force is summarized in table 5.

Table 5. Experiment 2: Linear Mixed Effect Models to Compare Laryngoscope Force among Intubation Sets

Type 3 Tests of Fixed Effects				
Effect	Numerator DF	Denominator DF	F Value	*P* Value
Subgroup (A, B)	1	18.1	1.00	0.3301
Laryngoscope (Macintosh, Airtraq)	1	11.5	56.36	<.0001
Intubation Set (1, 2, 3)	2	14.6	10.44	0.0015
Subgroup*Laryngoscope interaction	1	11.5	1.01	0.3352
Subgroup*Set interaction	1	14.4	1.89	0.1901
Subgroup*Laryngoscope*Set interaction	3	20.9	2.70	0.0720

Laryngoscope	Subgroup, Intubation Set	Total Force (N), Mean (SE)	Comparisons between Sets		
			Comparison conditions (tissue recovery time, temperature, C1-C2 stability)	Ratio: Set 2/Set 1 or Set 3/Set 2 (95% CI)	Bonferroni adjusted *P* value
Airtraq	A, Set 1	13.93 (4.34)	Baseline, warm, intact C1-C2		
	A, Set 2	5.17 (1.69)	Long recovery, cool, intact C1-C2	0.371 (0.149, 0.924)	0.028*
	A, Set 3	5.33 (1.74)	Short recovery, cool, injured C1-C2	1.030 (0.409, 2.597)	>0.99*
	B, Set 1	7.13 (3.14)	Baseline, warm, intact C1-C2		
	B, Set 2	3.44 (1.52)	Short recovery, warm, injured C1-C2	0.483 (0.159, 1.465)	0.350*
Macintosh	A, Set 1	47.23 (5.00)	Baseline, warm, intact C1-C2		
	A, Set 2	32.35 (3.43)	Long recovery, cool, intact C1-C2	0.685 (0.510, 0.919)	0.007*
	A, Set 3	29.70 (3.14)	Short recovery, cool, injured C1-C2	0.918 (0.684, 1.232)	>0.99*
	B, Set 1	38.11 (5.70)	Baseline, warm, intact C1-C2		
	B, Set 2	42.10 (6.30)	Short recovery, warm, injured C1-C2	1.105 (0.758, 1.611)	>0.99*
Overall	A, Set 2/Set 1		Long recovery, warm→cool,	0.504 (0.321, 0.791)	0.003†

		constant C1-C2 intact		
	A, Set 3/Set 2	Short recovery, constant cool, intact→injured C1-C2	0.973 (0.617, 1.533)	>0.99†
	B, Set 2/Set 1	Short recovery, constant warm, intact→injured C1-C2	0.730 (0.425, 1.254)	0.338†
	Pooled, Set 2/Set 1 (note confounding effects)		0.607 (0.455, 0.810)	0.002‡

Natural log (ln) transformation was utilized to normalize the force data distribution, with transformed data used in the analysis. Mean estimates were computed from the ln means by back-transformation, and corresponding standard error (SE) calculated by the delta method.

* For Bonferroni adjustment, reported *P* value is multiplied x 6 original (unadjusted) value.

† For Bonferroni adjustment, reported *P* value is multiplied x 3 original (unadjusted) value.

‡ Single comparison; reported *P* value is not adjusted.

The complete linear mixed effect model for the effect of repeated intubation on occiput-to-C5 (Oc-C5) extension is summarized in table 6.

Table 6. Experiment 2: Linear Mixed Effect Models to Compare Oc-C5 Extension among Intubation Sets

Type 3 Tests of Fixed Effects				
Effect	Numerator DF	Denominator DF	F Value	*P* Value
Subgroup (A, B)	1	19.2	0.22	0.6432
Laryngoscope (Macintosh, Airtraq)	1	17.2	39.02	<.0001
Intubation Set (1, 2, 3)	2	18.1	3.00	0.0751
Subgroup*Laryngoscope interaction	1	17.5	0.79	0.3858
Subgroup*Set interaction	1	17.8	0.28	0.6012
Subgroup*Laryngoscope*Set interaction	3	17.7	0.82	0.4992

Laryngoscope	Subgroup, Intubation Set	Oc-C5 Extension (degrees), Mean (SE)	Comparisons between Sets		
			Comparison conditions (tissue recovery time, temperature, C1-C2 stability)	Difference: Set 2 – Set 1 or Set 3 – Set 2 (95% CI)	Bonferroni adjusted *P* Value
Airtraq	A, Set 1	13.65 (2.20)	Baseline, warm, intact C1-C2		
	A, Set 2	5.36 (2.34)	Long recovery, cool, intact C1-C2	-8.28 (-17.30, 0.74)	0.085*
	A, Set 3	10.23 (2.34)	Short recovery, cool, injured C1-C2	4.86 (-4.38, 14.11)	0.842*
	B, Set 1	14.92 (3.12)	Baseline, warm, intact C1-C2		
	B, Set 2	5.90 (3.12)	Short recovery, warm, injured C1-C2	-9.02 (-20.16, 2.12)	0.149*
Macintosh	A, Set 1	28.48 (3.29)	Baseline, warm, intact C1-C2		
	A, Set 2	21.86 (3.29)	Long recovery, cool, intact C1-C2	-6.62 (-19.62, 6.38)	0.921*
	A, Set 3	23.50 (3.29)	Short recovery, cool, injured C1-C2	1.64 (-11.37, 14.64)	>0.99*
	B, Set 1	21.74 (4.66)	Baseline, warm, intact C1-C2		
	B, Set 2	21.19 (4.66)	Short recovery, warm, injured C1-C2	-0.55 (-17.19, 16.09)	>0.99*
Overall	A, Set 2 - Set 1		Long recovery, warm→cool, constant C1-C2 intact	-7.45 (-15.42, 0.52)	0.072†
	A, Set 3 - Set 2		Short recovery, constant cool, intact→injured C1-C2	3.25 (-4.77, 11.27)	0.896†

	B, Set 2 - Set 1	Short recovery, constant warm, intact→injured C1-C2	-4.78 (-14.78, 5.21)	0.513†
	Pooled, Set 2 - Set 1 (note confounding effects)		-6.12 (-11.39, -0.85)	0.025‡

* For Bonferroni adjustment, reported *P* value is multiplied x 6 original (unadjusted) value.

† For Bonferroni adjustment, reported *P* value is multiplied x 3 original (unadjusted) value.

‡ Single comparison; reported *P* value is not adjusted.

Experiment 3: Motion of an Injured C1-C2 Segment

Experiment 3, Control Measurements

C2 endplate length at the two preintubation baselines did not differ with either laryngoscope. Specifically, for the Macintosh (n=12) the difference in preintubation baseline (stage 1) C2 endplate length between injured (14.6±1.2 mm) and intact (14.4±1.4 mm) conditions equaled 0.2±0.6 mm; *P*=0.5186. For the Airtraq (n=11), the difference in preintubation baseline (stage 1) C2 endplate length between injured (14.6±1.5 mm) and intact conditions (14.5±1.5 mm) equaled 0.1±0.8 mm; *P*=1.000. Because preintubation baseline C2 endplate length did not differ between injured and intact states, reported linear distances have negligible errors due to differences among image sets in either cervical spine axial rotation or changes in angle of incidence between the x-rays source and spine.

C1-C2 intervertebral angle at the two pre-intubation baselines (injured C1-C2—stage 1 *vs.* intact C1-C2—stage 1) did not differ with either laryngoscope. Specifically, for the Macintosh (n=12), the difference in preintubation baseline (stage 1) C1-C2 intervertebral angle between injured and intact conditions (injured C1-C2 value minus intact C1-C2 value) equaled -1.7±5.6 degrees; *P*=0.3394. For the Airtraq (n=11), the difference in preintubation baseline (stage 1) C1-C2 intervertebral angle between injured and intact conditions equaled 0.4±4.1 degrees; *P*=0.7646. Because preintubation baseline C1-C2 intervertebral angle did not differ between the injured and intact states, C1-C2 extension can be reliably compared between these two states.

C1-C2 canal space at the two preintubation baselines did not differ with either laryngoscope. For the Macintosh (n=12) the difference in preintubation baseline (stage 1) C1-C2 canal space between injured (19.0±2.4 mm) and intact (19.6±1.4 mm) conditions equaled -0.7±2.1 mm; *P*=0.3804. For the Airtraq (n=11), the difference in preintubation baseline (stage 1) C1-C2 canal space between injured (18.9±2.7 mm) and intact conditions (19.4±1.5 mm) (injured C1-C2 value minus intact C1-C2 value) equaled -0.5±2.7 mm;

P=0.9658. Because preintubation baseline C1-C2 canal space did not differ between injured and intact states, C1-C2 canal space can be reliably compared between these two states.

Experiment 3, Primary Results

The complete linear mixed effect models for motion of the intact and injured C1-C2 segment with both Macintosh and Airtraq laryngoscopes are summarized in table 7.

Table 7. Experiment 3, Primary Results: Linear Mixed Effect Models to Compare C1-C2 Motion between Intact and Injured C1-C2

Variable	Type 3 Tests of Fixed Effects			C1-C2 motion comparison				
	Effect	F Value	*P* Value	Subgroup	Laryngoscope	Intact C1-C2 Mean (SE)	Injured C1-C2 Mean (SE)	Bonferroni adjusted *P* value
C1-C2 extension	Subgroup (A, B)	1.90	0.217	A	Airtraq	1.38 (1.32)	2.22 (1.32)	>0.99*
	Laryngoscope (Macintosh, Airtraq)	7.20	0.020		Macintosh	2.76 (1.25)	7.43 (1.25)	0.015*
	Subgroup*Laryngoscope interaction	0.17	0.690		Average	Difference (Intact-Injured): -2.76 (95% CI: -5.28, -0.24)		0.031†
	C1-C2 (Injured, Intact)	0.06	0.816	B	Airtraq	4.70 (2.67)	2.06 (2.67)	>0.99*
	Subgroup*C1-C2 interaction	2.80	0.121		Macintosh	8.61 (2.67)	7.11 (2.67)	>0.99*
	Laryngoscope*C1-C2 interaction	0.74	0.407		Average	Difference (Intact-Injured): 2.07 (95% CI: -5.16, 9.31)		0.923†
	Subgroup*Laryngoscope *C1-C2 interaction	0.22	0.648	Pooled	Airtraq	Difference (Intact-Injured): 0.90 (95% CI: -4.35, 6.15)		>0.99†
					Macintosh	Difference (Intact-Injured): -1.59 (95% CI: -6.82, 3.65)		0.90†
					Average	Difference (Intact-Injured): -0.34 (95% CI: -3.50, 2.81)		0.816‡
					Difference (Airtraq-Macintosh)	-2.64 (95%CI: -7.89, 2.61) *P*=0.443†	-5.13 (95%CI: -10.37, 0.12) *P*=0.056†	
Change C1-C2 canal	Subgroup (A, B)	6.06	0.033	A	Airtraq	-0.13 (0.46)	-0.49 (0.46)	>0.99*
	Laryngoscope (Macintosh, Airtraq)	0.02	0.900		Macintosh	-0.77 (0.43)	-0.82 (0.43)	>0.99*
	Subgroup*Laryngoscope	2.22	0.147		Average	Difference (Intact-Injured):		>0.99†

	interaction					0.21 (95% CI: -0.78, 1.19)		
	C1-C2 (Injured, Intact)	1.22	0.278	B	Airtraq	-1.34 (0.61)	-2.56 (0.61)	0.558*
	Subgroup*C1-C2 interaction	0.27	0.606		Macintosh	-1.41 (0.61)	-1.34 (0.61)	>0.99*
	Laryngoscope*C1-C2 interaction	1.31	0.262		Average	Difference (Intact-Injured): 0.58 (95% CI: -0.77, 1.92)		0.643†
	Subgroup*Laryngoscope *C1-C2 interaction	0.48	0.492	Pooled	Airtraq	Difference (Intact-Injured): 0.80 (95% CI: -0.40, 1.99)		0.253†
					Macintosh	Difference (Intact-Injured): -0.01 (95% CI: -1.18, 1.15)		>0.99†
					Average	Difference (Intact-Injured): 0.39 (95% CI: -0.33, 1.11)		0.278‡
					Difference (Airtraq-Macintosh)	0.36 (95%CI: -0.82, 1.54) *P*=0.956†	-0.45 (95%CI: -1.63, 0.73) *P*=0.752†	

Variable	Type 3 Tests of Fixed Effects			C1-C2 motion comparison				
	Effect	F Value	*P* Value	Subgroup	Laryngoscope	Intact C1-C2 Mean (SE)	Injured C1-C2 Mean (SE)	Bonferroni adjusted *P* value
C1-C2 canal	Subgroup (A, B)	1.50	0.242	A	Airtraq	19.27 (0.47)	18.44 (0.88)	>0.99*
	Laryngoscope (Macintosh, Airtraq)	0.01	0.914		Macintosh	18.92 (0.43	18.29 (0.81)	>0.99*
	Subgroup*Laryngoscope interaction	1.61	0.233		Average	Difference (Intact-Injured): 0.73 (95% CI: -1.67, 3.13)		0.836†
	C1-C2 (Injured, Intact)	1.71	0.231	B	Airtraq	18.35 (0.66)	16.74 (1.23)	0.99*
	Subgroup*C1-C2 interaction	0.10	0.762		Macintosh	18.15 (0.61)	17.36 (1.15)	>0.99*
	Laryngoscope*C1-C2 interaction	2.84	0.114		Average	Difference (Intact-Injured): 1.20 (95% CI: -2.19, 4.58)		0.705†
	Subgroup*Laryngoscope *C1-C2 interaction	1.07	0.319	Pooled	Airtraq	Difference (Intact-Injured): 1.22 (95% CI: -1.01, 3.45)		0.326†
					Macintosh	Difference (Intact-Injured): 0.71 (95% CI: -1.27, 2.69)		0.711†
					Average	Difference (Intact-Injured): 0.96 (95% CI: -0.77, 2.69)		0.231‡
					Difference	0.27 (95%CI:	-0.23 (95%CI:	

					(Airtraq-Macintosh)	-0.16, 0.70) P=0.235†	-0.97, 0.50) P=0.875†	
C2 canal	Subgroup (A, B)	0.14	0.719	A	Airtraq	15.88 (0.62)	16.28 (0.62)	0.148*
	Laryngoscope (Macintosh, Airtraq)	0.04	0.846		Macintosh	15.84 (0.62)	16.19 (0.62)	0.198*
	Subgroup*Laryngoscope interaction	0.40	0.540		Average	Difference (Intact-Injured): -0.37 (95% CI: -0.66, -0.08)		0.013†
	C1-C2 (Injured, Intact)	1.01	0.336	B	Airtraq	15.63 (0.68)	15.68 (0.68)	>0.99*
	Subgroup*C1-C2 interaction	1.81	0.203		Macintosh	15.87 (0.68)	15.71 (0.68)	>0.99*
	Laryngoscope*C1-C2 interaction	0.17	0.685		Average	Difference (Intact-Injured): 0.05 (95% CI: -0.73, 0.84)		>0.99†
	Subgroup*Laryngoscope *C1-C2 interaction	0.07	0.800	Pooled	Airtraq	Difference (Intact-Injured): -0.22 (95% CI: -0.79, 0.35)		0.675†
					Macintosh	Difference (Intact-Injured): -0.09 (95% CI: -0.66, 0.48)		>0.99†
					Average	Difference (Intact-Injured): -0.16 (95% CI: -0.50, 0.18)		0.336‡
					Difference (Airtraq-Macintosh)	-0.10 (95%CI: -0.67, 0.47) P>0.99†	0.03 (95%CI: -0.54, 0.60) P>0.99†	

Natural log (ln) transformation was utilized to normalize the force data distribution, with transformed data used in the analysis. Mean estimates were computed from the ln means by back-transformation, and corresponding standard error (SE) calculated by the delta method.

* For Bonferroni adjustment, reported *P* value is multiplied x 4 original (unadjusted) value.

† For Bonferroni adjustment, reported *P* value is multiplied x 2 original (unadjusted) value.

‡ Single comparison; reported *P* value is not adjusted.

Experiment 3, "Force Corrected" Results

The complete linear mixed effect models for "force corrected" motion of the intact and injured C1-C2 segment with both Macintosh and Airtraq laryngoscopes are summarized in table 8.

Table 8. Experiment 3, "Force Corrected" Results: Linear Mixed Effect Models to Compare C1-C2 Motion between Intact and Injured C1-C2

Variable	Type 3 Tests of Fixed Effects			C1-C2 motion comparison				
	Effect	F Value	*P* Value	Subgroup	Laryngoscope	Intubation Set 1 Intact C1-C2 Mean (SE)	"Force Corrected" Injured C1-C2 Mean (SE)	Bonferroni adjusted *P* value
C1-C2 extension	Subgroup (A, B)	0.21	0.662	A	Airtraq	5.16 (1.87)	3.73 (1.98)	>0.99*
	Laryngoscope (Macintosh, Airtraq)	3.17	0.100		Macintosh	7.12 (1.87)	11.76 (1.87)	0.205*
	Subgroup*Laryngoscope interaction	0.26	0.617		Average	Difference (Intact-Injured): -1.60 (95% CI: -5.51, 2.31)		0.666†
	C1-C2 (Injured, Intact)	0.00	0.951	B	Airtraq	4.70 (3.87)	4.52 (3.87)	>0.99*
	Subgroup*C1-C2 interaction	0.45	0.514		Macintosh	8.61 (3.87)	6.14 (3.87)	>0.99*
	Laryngoscope*C1-C2 interaction	0.19	0.672		Average	Difference (Intact-Injured): 1.33 (95% CI: -9.54, 12.19)		>0.99†
	Subgroup*Laryngoscope *C1-C2 interaction	0.92	0.365	Pooled	Airtraq	Difference (Intact-Injured): 0.81 (95% CI: -7.09, 8.71)		>0.99†
					Macintosh	Difference (Intact-Injured): -1.08(95% CI: -8.97, 6.80)		>0.99†
					Average	Difference (Intact-Injured): -0.14 (95% CI: -4.89, 4.61)		0.951‡
					Difference (Airtraq-Macintosh)	-2.94 (95%CI: -10.82 4.95) *P*=0.717†	-4.83 (95%CI: -12.73, 3.08) *P*=0.288†	
Change C1-C2 canal	Subgroup (A, B)	4.32	0.064	A	Airtraq	-0.59 (0.76)	-1.29 (0.82)	>0.99*
	Laryngoscope (Macintosh, Airtraq)	4.79	0.037		Macintosh	-0.63 (0.76)	-1.07 (0.76)	>0.99*
	Subgroup*Laryngoscope interaction	4.17	0.050		Average	Difference (Intact-Injured): 0.57 (95% CI: -1.15, 2.29)		0.878†

	C1-C2 (Injured, Intact)	5.35	0.028	B	Airtraq	-1.34 (1.08)	-6.34 (1.08)	0.003*
	Subgroup*C1-C2 interaction	1.95	0.173		Macintosh	-1.41 (1.08)	-1.01 (1.08)	>0.99*
	Laryngoscope*C1-C2 interaction	5.19	0.030		Average	Difference (Intact-Injured): 2.30 (95% CI: -0.08, 4.69)		0.059†
	Subgroup*Laryngoscope *C1-C2 interaction	4.31	0.047	Pooled	Airtraq	Difference (Intact-Injured): 2.85 (95% CI: 0.76, 4.94)		0.006†
					Macintosh	Difference (Intact-Injured): 0.02 (95% CI: -2.04, 2.08)		>0.99†
					Average	Difference (Intact-Injured): 1.44 (95% CI: 0.17, 2.71)		0.028‡
					Difference (Airtraq-Macintosh)	0.06 (95%CI: -2.01, 2.12) *P* >0.99†	-2.77 (95%CI: -4.86, -0.69) *P*=0.008†	

Variable	Type 3 Tests of Fixed Effects			C1-C2 motion comparison				
	Effect	F Value	*P* Value	Subgroup	Laryngoscope	Intubation Set 1 Intact C1-C2 Mean (SE)	"Force Corrected" Injured C1-C2 Mean (SE)	Bonferroni adjusted *P* value
C1-C2 canal	Subgroup (A, B)	3.71	0.085	A	Airtraq	20.71 (0.74)	17.82 (1.31)	0.048*
	Laryngoscope (Macintosh, Airtraq)	4.50	0.060		Macintosh	20.30 (0.81)	18.03 (0.61)	0.078*
	Subgroup*Laryngoscope interaction	5.31	0.044		Average	Difference (Intact-Injured): 2.58 (95% CI: 0.88, 4.29)		0.005†
	C1-C2 (Injured, Intact)	24.63	0.0006	B	Airtraq	18.35 (1.04)	12.96 (1.80)	0.008*
	Subgroup*C1-C2 interaction	0.10	0.763		Macintosh	18.15 (1.14)	17.69 (0.87)	>0.99*
	Laryngoscope*C1-C2 interaction	7.74	0.021		Average	Difference (Intact-Injured): 2.92 (95% CI: 0.55, 5.30)		0.018†
	Subgroup*Laryngoscope *C1-C2 interaction	4.67	0.059	Pooled	Airtraq	Difference (Intact-Injured): 4.14 (95% CI: 2.05, 6.23)		0.0008†
					Macintosh	Difference (Intact-Injured): 1.37 (95% CI: -0.50, 3.23)		0.165†
					Average	Difference (Intact-Injured): 2.75 (95% CI: 1.52, 3.99)		0.0006‡
					Difference	0.30 (95%CI:	-2.47 (95%CI:	

			(Airtraq-Macintosh)	-0.09, 0.69) P=0.136†	-5.12, 0.18) P=0.068†	

Natural log (ln) transformation was utilized to normalize the force data distribution, with transformed data used in the analysis. Mean estimates were computed from the ln means by back-transformation, and corresponding standard error (SE) calculated by the delta method.

* For Bonferroni adjustment, reported *P* value is multiplied x 4 original (unadjusted) value.

† For Bonferroni adjustment, reported *P* value is multiplied x 2 original (unadjusted) value.

‡ Single comparison; reported *P* value is not adjusted.

Discussion

Limitations

As shown in Figure 2, Panel A, in an isolated intact vertebral segment starting at neutral position, initial low values of load (*e.g.*, force) result in displacement (*e.g.*, flexion, extension, rotation…) in an essentially linear fashion. This first phase is commonly referred to as the neutral zone. Thereafter, there is a progressive decrease in the amount of displacement per unit change in load until displacement reaches an upper physiologic boundary. This second phase is commonly referred to as the elastic zone. Studies in isolated cervical vertebral segments show that progressive injury results in an increase in the neutral zone and an increase in the total range of motion.[2]

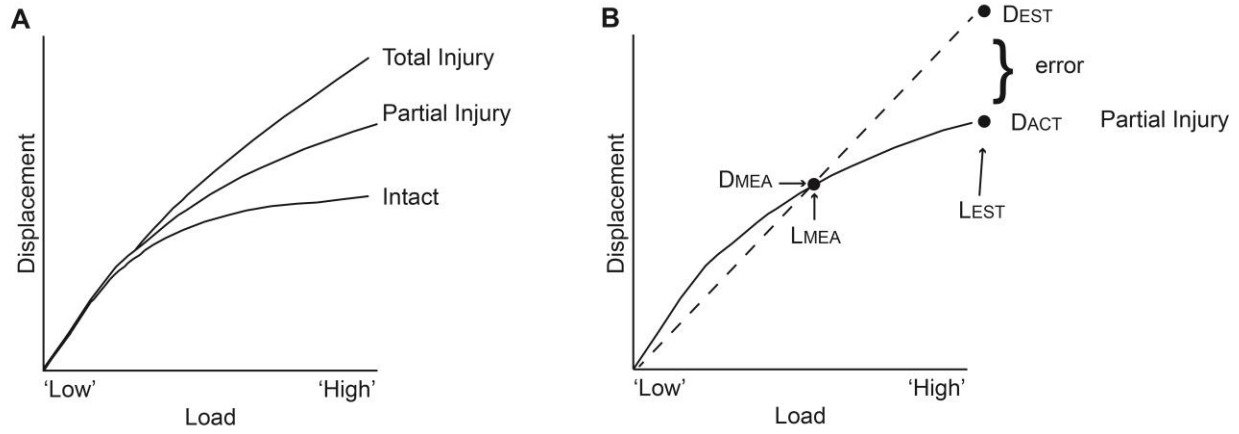

Fig 2. Panel A provides examples of idealized load-displacement curves in isolated vertebral segments that are intact, and those with partial and total injury. Panel B, shows the method of "force correction" used in this study. Using the experimentally measured load (L_{MEA}) [intubation force] and experimentally measured displacement (D_{MEA}) [extension, subluxation], a linear relationship was assumed in order to estimate the displacement (D_{EST}) of the partially injured C1-C2 segment at greater estimated loads (L_{EST}) [intubation force], resulting in "force corrected" displacement (motion) values. The difference between D_{EST} and the displacement that would have actually occurred (D_{ACT}) if the load had been applied experimentally is the error of the estimate.

Thus, as shown in Figure 2, Panel A, one can imagine a family of three types of load-displacement curves: 1) Intact; 2) Partial Injury; and 3) Total Injury. The Partial Injury curve will have a greater neutral zone and greater range of motion than the intact curve,

but will continue to demonstrate some limitation of motion because of the integrity of remaining supportive structures. The Total Injury curve will be essentially a straight line, with much greater range of motion. However, for all three curves, the load-displacement relationship at low loads will be nearly identical because motion is essentially unrestricted in the neutral zone. Thus, at low loads, the load-displacement curves of an intact and injured vertebral segment will be difficult to distinguish. Only at greater loads do the curves diverge, and might be distinguishable from one another experimentally.

The methodological challenge was to determine the load-displacement curves of the partially injured C1-C2 segments that would allow us to predict the motions of the injured C1-C2 segments at intubation forces greater than those measured experimentally. We determined that was not possible, particularly when motion data was derived only from low applied forces (nearly linear responses in the neutral zone). Therefore, the only option was to assume each <u>partially</u> injured C1-C2 segment behaved like a <u>totally</u> injured segment, with a linear load-displacement curve over the entire range of forces.

The effect of such an assumption is shown in Figure 2, Panel B, in which the estimated displacement (D_{EST}) is greater than the actual displacement (D_{ACT}) that would have occurred if the estimated load (L_{EST}) had actually been applied. The potential for over-estimation of displacement will depend, at least in part, on the ratio of the estimated load to measured load (L_{EST}/L_{MEA}). With the Macintosh, overall, the ratio of estimated force (load) (L_{EST} =45.6 N) to measured force (load) (L_{MEA} =35.2 N) was 1.29. With the Airtraq the L_{EST}/L_{MEA} ratio was (14.3/6.0 N) 2.38. Thus, a much greater proportional "correction" was necessary with Airtraq data compared with Macintosh data. Hence, the likelihood of an overestimation error was greater with "force corrected" Airtraq data. However, the amount of "force corrected" subluxation with 14.3 N of force with the Airtraq is nearly identical to the subluxation that was measured directly in an *in vitro* odontoid fracture model (3 mm of subluxation with 10 N of anterior force).[3] Therefore, "force corrected" values for Airtraq C1-

C2 subluxation in the presence of a Type II odontoid fracture are consistent with findings from independent study using entirely different methods.

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