Predictive models for difficult laryngoscopy and intubation. A clinical, radiologic and three-dimensional computer imaging study

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Purpose: To identify the variables most useful in predicting difficult laryngoscopy and intubation from various clinical, skeletal (lateral x-rays) and soft tissue (three-dimensional computed tomography imaging) measurements.

Methods: Twenty-four adult patients in whom an unanticipated difficult tracheal intubation was identified according to established criteria were evaluated. Further, a control group of 32 patients in whom tracheal intubation was easily accomplished was studied. We applied multivariate discriminant analysis to clinical and radiological data of all patients to select those variables most useful in predicting difficult laryngoscopy and intubation. The receiver operating characteristic (ROC) curve was used to describe the discrimination abilities and to explore the trade-offs between sensitivity and specificity of the model.

Results: With the clinical data alone, discriminant analysis identified four risk factors that correlated with the prediction of difficult laryngoscopy and intubation: thyrosternal distance, thyromental distance, neck circumference and Mallampati classification. With both clinical and radiological data, discriminant analysis identified five risk factors: thyrosternal distance, thyromental distance, Mallampati classification, depth of spine C2 and angle A (the most antero-inferior point of the upper central incisor tooth). The positive predictive value of this combined (clinical and radiological) model was greater than that of the clinical model alone (95.8% vs 87.5%, respectively). The areas under the ROC curves, that measure the probability of the correct prediction of the clinical and the combined models, were found to be 0.933 and 0.973, respectively.

Conclusions: These models can be used for predicting difficult laryngoscopy and intubation in clinical practice.

Objectif : Identifier les variables les plus utiles servant à prédire des difficultés de laryngoscopie et d'intubation à partir de diverses mesures cliniques, squelettiques (radiographies de profil) et des tissus mous (tomodensitométrie en trois dimensions).

Méthode : On a évalué 44 patients adultes pouvant présenter, selon des critères reconnus, une intubation endotrachéale difficile imprévue. En contrepartie, on a étudié un groupe témoin de 32 patients chez qui l'intubation avait été facilement réalisée. L'analyse multifactorielle discriminante des données cliniques et radiologiques de tous les patients a permis de sélectionner les variables les plus utiles pour prédire la laryngoscopie et l'intubation difficiles. L'analyse par les courbes ROC (Receiver Operating Characteristic) a été utilisée pour décrire les possibilités de discrimination et explorer les recoupements entre la sensibilité et la spécificité du modèle.

Résultats : L'analyse discriminante des données cliniques permet d'identifier quatre facteurs de risque en corrélation avec la prédiction de laryngoscopie et d'intubation difficiles : la distance thyrosternale, la distance thyromentonnière, le périmètre du cou et la classification de Mallampati. L'analyse des données cliniques et radiologiques réunies indique cinq facteurs de risque : la distance thyrosternale, la distance thyromentonnière, la classification de Mallampati, la profondeur de la vertèbre C2 et l'angle A (le point le plus antéro-inférieur de la dent incisive centrale supérieure). La valeur prédictive positive de ce modèle combiné (clinique et radiologique) est meilleure que celle du modèle clinique seul (95,8 % vs 87,5 %, respectivement). Les aires sous les courbes ROC, qui mesurent la probabilité de prédiction exacte des modèles clinique et combiné, étaient de 0,933 et 0,973 respectivement.

Conclusion : Les modèles décrits peuvent être utilisés pour prédire la laryngoscopie et l'intubation difficiles en pratique clinique.

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ALTHOUGH unanticipated difficult intubation continues to be a cause of morbidity and mortality in clinical practice, the predictive factors of difficult laryngoscopy have not been completely identified. Difficult tracheal intubation accounted for approximately 17% of the adverse respiratory events in the ASA closed claims analysis.[1] The incidence of difficult intubation in non-obstetric surgical patients has been reported as varying from 0.05% to 2%.[2-4] The literature, however, frequently confuses difficulty of laryngoscopy with difficult tracheal intubation.[5] In most studies, difficult laryngoscopy is defined as that resulting in a view of the larynx corresponding to Cormack and Lehane grades 3 and 4.[6] This occurs during 0.3-13% of laryngoscopies.[2,5,7]

On the other hand, there is no generally accepted definition of difficult intubation. The American Society of Anesthesiologists (ASA) has defined difficult tracheal intubation as when "proper insertion of the endotracheal tube with conventional laryngoscopy requires more than three attempts, or more than ten minutes."[8] Other proposed definitions include failure to intubate, more than two laryngoscopies, more than three attempts in the modified Jackson position, poor visualization of the vocal cords, and a combination of subjective evaluation and number of laryngoscopies.[4,6,9-11]

Difficult intubation has been attributed to several unfavourable anatomical factors such as receding mandible, protruding upper incisors and long maxilla, limited mobility of the temporomandibular joint,[2,12] small atlanto- occipital gap,[13,14] restricted pharyngeal space, and reduced submandibular tissue compliance.[15] In a retrospective radiological survey of subjects who presented difficulty in tracheal intubation, Bellhouse and Doré reported that the most important features relevant to difficulty were reduced atlanto-occipital extension, reduced mandibular space and increased anteroposterior thickness of the tongue.[16] However, the results of the latter study[16] have not been substantiated. Simple bed-side tests, such as Mallampati test,[10] thyromental distance,[17] sternomental distance[18] and Wilson risk sum score,[1] were found to be of limited use as predictors of difficult laryngoscopy.[3,7,19,20]

As difficult laryngoscopy is a multifactorial problem, it is clear that no simple test can be used alone and effective prediction requires a combination of tests. Nevertheless, no clinical test or system of tests (multifactorial prediction indexes) has proved to be completely sensitive or specific for the difficult laryngoscopic intubation.[15,21,22]

Recently, helical scan computed tomography (CT) has become available to provide a three-dimensional imaging (3D-CT) of different anatomical structures including the airway.[23,24] We have used this technique to evaluate the airway of patients in this study.

In this study we evaluated all known clinical and radiological airway risk criteria. We applied multivariate discriminant analysis to these criteria in a group of patients with confirmed difficult laryngoscopy and intubation and a control group with easy laryngoscopy and intubation in order to select those variables most useful in predicting difficult laryngoscopy and intubation. For the purposes of this study, a difficult laryngoscopy was defined as that resulting in a view of the larynx with a Macintosh laryngoscope corresponding to Cormack and Lehane grades 3 and 4 that resulted in difficult tracheal intubation. The latter was defined as one that involves three or more attempts to place the endotracheal tube by a consultant anesthesiologist.

Methods

The department of Anesthesiology at King Khalid University Hospital, Riyadh, Saudi Arabia, developed a local database of patients in whom laryngoscopy and tracheal intubation have proved difficult. A data entry form is completed (prospectively) when a difficult intubation arises. This records demographic information on the patient and attending physicians as well as providing details of the nature of the difficulty, e.g., the details of the laryngoscopy findings and the degree of difficulty of intubation, equipment used, and whether anesthesia and surgery were continued.

After obtaining institutional approval, we retrieved the detailed information of patients from our database. Thirty-seven patients in whom an unanticipated difficult intubation was identified and were scheduled to undergo endotracheal anesthesia for any type of nonemergency surgical procedures except traumatic facial abnormalities or obstetric and cardiac surgery between January 1996 and June 1998 were identified. In these patients, senior anesthesiologists (with a minimum of 10 yr anesthetic experience) experienced difficult laryngoscopy (corresponding to Cormack and Lehane grades 3 and 4) and difficult tracheal intubation (three or more attempts to place the endotracheal tube) when using optimal head and neck positioning (the sniffing position). When contacted by telephone, 25 patients (group 1) agreed to participate in the study. Study patients met the following criteria: mentally competent adult; not pregnant; ASA physical status I or II. None of these patients was edentulous, had an obvious anatomical pathology, disease of the cervical spine or required cricoid pressure for rapid-sequence intubation. A control group (group 2) of patients (n= ,32), in whom laryngoscopy and intubation was found to be easy and anesthetized by the same anesthesiologists, was randomly recruited to participate in the study.

All patients (n = 57) were given appointments for radiographic studies, which included lateral radiographs and a three-dimensional computed tomography scans. On the day of the radiological studies, clinical assessment was carried out in all patients by one investigator who was not involved in their anesthetic management. Informed consent was obtained from all patients. The details of the laryngoscopy findings and the degree of difficulty of intubation were not known to this investigator at this time.

The clinical assessment included:

1. Weight, height and age.
2. The airway was assessed according to the pharyngeal structures seen, using the method described by Mallampati[10] with the modification of Samsoon and Young[4]:
   Class 1 - soft palate, fauces, uvula and pillars visible.
   Class 2 - soft palate, fauces, uvula visible.
   Class 3 - soft palate, base of uvula visible.
   Class 4 - none of the soft palate visible.
3. Interincisor gap measured with the mouth fully open.
4. Thyromental distance was measured along a straight line from the thyroid notch to the lower border of the mandibular mentum with the head fully extended and the mouth closed.
5. Thyrosternal distance was measured along a straight line from the thyroid notch to the upper border of the manubrium sterni with the head fully extended and the mouth closed.
6. Neck circumference.
7. Wilson risk sum score. This scores five factors (weight, head and neck movement, jaw movement, receding mandible and buck teeth) from 0 to 2, giving a total ranging from 0 to 10 (Table I).[2]

The *radiological assessment* included:

Lateral x-rays of the head and neck were taken at a distance of two metres. First, with the head erect and mouth closed, and then with the head fully extended on the neck, the mouth fully opened, and the tongue relaxed in a neutral position between protrusion and retraction. Specific measurements were made as described by Bellhouse and Doré[16] and by Chou and Wu.[25] The various distances that were measured are shown in Figures 1 and 2 and described in the legends. As all radiographs were taken at the same distance, the magnification factor was constant (20%). The magnification factor was determined by a metallic centimeter marker that was strapped to the chin in the midline to provide direct measuring scale on a pilot film. The actual measurements on the radiographs were tabulated and, thus, the lengths (but not the angles and ratios) were 20% larger than actual.

Three-dimensional imaging (3D-CT):

A Somatom Plus-S unit (Siemens, Forchheim, Germany) was used to perform 3D-CT scans. The following measurements were made on each 3D-CT scan: (1) distance from most posterior aspect of the base of the tongue to the posterior pharyngeal wall; (2) distance between most posterior aspect of the epiglottis and the posterior pharyngeal wall; (3) distance between tip of the uvula and posterior pharyngeal wall; (4) distance between the uppermost visible part of the airway at the level of the vocal cords and posterior pharyngeal wall at the level of the piriform sinuses; (5) length of epiglottis; (6) angle between the epiglottis and the tongue; (7) angle between the long axes of the pharynx and larynx; and (8) angle between long axes of larynx and trachea. The points of measurement of these parameters are shown in Figures 3-6. Measurements obtained from 3D-CT scans were exact without magnification.

All 3D-CT scans and radiographs were measured by an experienced radiologist (TM) in batches containing patients from both groups. Bias was avoided because the radiologist was blind as to whether the radiograph belonged to a patient in group 1 or group 2. The spread in the results was such that little if any pattern was obvious prior to data analysis.

TABLE I Wilson risk sum score2

Risk factor	*Level*	
Weight	0	< 90 kg
	1	90-110 kg
	2	> 110 kg
Head and neck movement	0	Above 90°
	1	About 90° (ie. ± 10°)
	2	Below 90°
Jaw movement	0	IG ≥ 5 cm or SLux > 0
	1	IG < 5 cm and SLux = 0
	2	IG < 5 cm and SLux < 0
Receding mandible	0	Normal
	1	Moderate
	2	Severe
Buck teeth	0	Normal
	1	Moderate
	2	Severe

IG = Inter-incisor gap.
SLux = Subluxation (maximal forward protrusion of the lower incisors beyond the upper incisors).

Data processing and statistical analyses

All statistical analyses were carried out using the BMDP statistical package, release 7.01 (University of California Press, Berkeley, CA, USA, 1994). First, we subjected the clinical measurements alone, then the radiological measurements alone and lastly both the clinical and radiological measurements to multivariate discriminant analysis based on a stepwise, forward and backward selection of variables according to their predictive ability. An allocation rule based on the mean scores of each group was developed. Variables that are predictors of difficult intubation were identified. These predictions were then compared with the actual outcome in every patient.

The receiver operating characteristic (ROC) curve was also used to describe the discrimination abilities and to explore the trade-offs between sensitivity and specificity of our model. The ROC curve is constructed from a set of (x,y) points, where x = the proportion of false positive results (1 - specificity) and y = the proportion of true positive results (sensitivity). The most commonly used quantitative index to describe the ROC curve is the area under the curve.[26] The ROC area ranges from 0.5 (corresponding to a totally uninformative variable) to 1.0 (corresponding to a variable which classifies perfectly).

Differences between the two groups were determined using Mann-Whitney rank-sum test and were considered significant when $P < 0.05$.

Results

One patient in the difficult laryngoscopy and intubation group was excluded because some of his radiographs were missing. All patients had full sets of teeth. Of the 24 difficult patients, in 23 the tracheas were successfully intubated after multiple attempts and changing blades. In one patient (Cormack and Lehane grade IV), tracheal intubation was successful with the aid of fibreoptic bronchoscopy. The demographic data of both groups are shown in Table II. There was an association between age and height and difficult laryngoscopy and intubation. Patients who had a reduced laryngoscopic view and difficult intubation were older and shorter (Table II). Interincisor gap, thyromental distance, thyrosternal distance, Mallampati's modified test, Wilson sum risk score and neck circumference were also different between the two groups (Table II).

Numerical values for the measured radiographs and 3D-CT scan parameters are shown in Table III. Univariate analysis identified ten measurements that differed between the two groups (Table III).

With the clinical data alone, discriminant analysis identified four risk factors that correlated with the predication of difficult laryngoscopy and intubation: thyrosternal distance, thyromental distance, neck circumference and Mallampati classification. Pairwise test of equality of group means was statistically significant (Table II). The discriminant function for clinical criteria alone (l) is given by:

$$l = 4.9504+(\text{thyrosternal distance } \times 1.1003)+(\text{Mallampati} \times -2.6076)+(\text{thyromental distance} \times 0.9684)+(\text{neck circumference} \times -0.3966) \qquad (1)$$

The posterior probability of group membership for each patient was used to compare the model prediction with the actual outcome. The sensitivity and specificity of the clinical model were found to be, respectively, 95.4 and 91.2%. Three patients were predicted as difficult for tracheal intubation when actually their tracheas

TABLE II Univariate analysis of clinical variables. (mean ± SD), number or range

	Difficult laryngoscopy and intubation group (n = 24)	*Easy laryngoscopy and intubation group (n = 32)*	*P*
Age (yr)	42.2 ± 12.4	32.9 ± 10.9	< 0.01
Sex (M/F)	14/8	25/7	0.11
Weight (kg)	77.4 ± 19	73.7 ± 12	0.3
Height (cm)	161.7 ± 11.3	166.4 ± 5.7	< 0.05
Inter-incisor gap (IG) (cm)	3.9 ± 0.9	4.5 ± 0.7	< 0.01
Thyromental distance (cm)	6.45 ± 1.6	7.6 ± 0.9	< 0.01
Thyrosternal distance (cm)	7.1 ± 1.7	8.8 ± 1.1	< 0.0001
Mallampati=s modified test:			
Class 1	1	17	< 0.0001
Class 2	14	14	
Class 3	8	1	
Class 4	1	0	
Wilson risk sum score	2 (0-5)	0.6 (0-2)	< 0.001
Neck circumference (cm)	39.4 ± 3.1	37.2 ± 2.8	< 0.05

TABLE III Univariate analysis of radiologic and 3D-CT scans measurements. (mean ± SD)

	Difficult laryngoscopy and intubation group (n = 24)	*Easy laryngoscopy and intubation group (n = 32)*	*P*
V1 (cm)	10.5 ± 0.9	10.8 ± 0.8	0.4
V2 (cm)	3.4 ± 0.5	3.6 ± 1.4	0.7
V3 (cm)	9.6 ± 0.9	9.4 ± 2.1	0.5
V4 (cm)	4.1 ± 0.9	4.2 ± 0.8	0.3
V5 (cm)	10.1 ± 0.9	10.4 ± 0.9	0.5
V6 (cm)	2.5 ± 0.4	2.6 ± 0.6	0.5
V7 (cm)	4 ± 1.2	3.9 ± 0.6	0.8
V8 (cm) (IG)	3.8 ± 0.9	4.7 ± 0.9	< 0.001
V9 (cm)	8.2 ± 0.9	8.6 ± 0.5	0.053
V10 (mm)	3.1 ±2.2	3.4 ± 2.6	0.8
V11 (mm)	10.8 ± 3	10 ± 1.3	0.4
V12 (mm)	3.4 ± 1.6	4.1 ± 1.7	0.09
V13 (mm)	17.3 ± 3.1	15.7 ± 3.7	0.09
V14 (degrees)	11.9 ± 3.4	14.6 ± 2.9	< 0.01
V15 (cm)	2.5 ± 0.6	3.1 ± 0.6	< 0.001
V16 (cm)	5 ± 0.8	5.5 ± 1	0.09
V17 (cm)	14.1 ± 1.7	15.1 ± 1.4	< 0.05
V18 (cm)	3.7 ± 0.5	3.5 ± 0.8	0.2
V19 (cm)	6.1 ± 0.7	6.4 ± 0.9	0.3
V20 (degrees)	33 ± 4.5	31.4 ± 5	0.2
V21 (degrees)	115 ± 5.5	120 ± 7.5	< 0.05
V22 (degrees)	31 ± 3.7	28.5 ± 3.9	< 0.01
Ratio V14/V18	3.2 ± 0.9	4.6 ± 2.3	< 0.01
Ratio V15/V16	0.5 ± 0.1	0.6 ± 0.1	< 0.01
Ratio V16/V18	1.4 ± 0.2	1.7 ± 0.7	0.07
Ratio V16/V19	0.8 ± 0.1	0.9 ± 0.2	0.5
Ratio V19/V18	1.7 ± 0.2	2 ± 1	0.2
Mandibular angle (degrees)	73 ± 13	76 ± 12	0.4
Mandibulohyoid distance (mm)	18.3 ± 5.7	16.5 ± 5	0.2
Distance between base of the tongue and the posterior pharyngeal wall (cm)	1.6 ± 0.6	1.9 ± 0.6	< 0.05
Distance between epiglottis and the posterior pharyngeal wall (cm)	0.98 ± 0.4	1.1 ± 0.4	0.4
Distance between tip of the uvula and posterior pharyngeal wall (cm)	1.3 ± 0.4	1.4 ± 0.4	0.1
Distance between the vocal cords and posterior pharyngeal wall (cm)	1 ± 0.4	1 ± 0.2	0.9
Length of epiglottis (cm)	2.1 ± 0.9	1.9 ± 0.7	0.4
Angle between epiglottis and tongue (degrees)	43 ± 20	52 ± 18	< 0.05
Angle between pharynx andlarynx (degrees)	158 ± 7	159 ± 6	0.6
Angle between larynx and trachea (degrees)	157 ± 17	155 ± 19	0.9

were intubated easily, and one patient was falsely predicted to have easy laryngoscopy and intubation.

With both clinical and radiological data, discriminant analysis identified five risk factors that correlated with the predication of difficult laryngoscopy and intubation: thyrosternal distance, thyromental distance, Mallampati classification, depth of spine C2 (V13) and angle A (V20; The most antero-inferior point of the upper central incisor tooth). The discriminant function for both clinical and radiological criteria (l) is given by:

$$l = -10.2717 + (\text{thyrosternal distance} \times 1.2422) + (\text{Mallampati} \times -3.368) + (\text{thyromental distance} \times 0.966) + (\text{depth of spine C2} \times -0.3192) + (\text{angle A} \times 0.176) \quad (2)$$

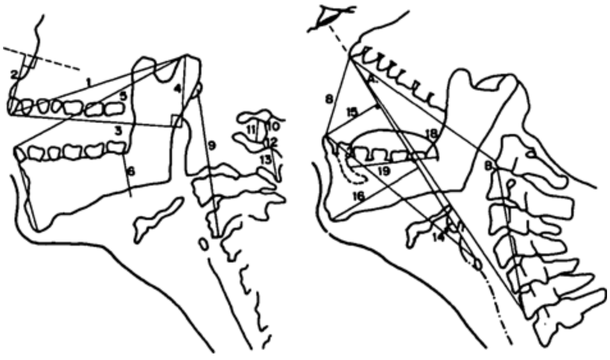

FIGURE 1 Illustrates the measurements that were made as follows: V1, temporomandibular joint (TMJ) to tip of upper incisors; V2, length of the perpendicular from the hard palate to the tip of the upper incisors; V3, length of line along the upper teeth to a perpendicular from the TMJ; V4, length of the perpendicular to this line; V5, TMJ to tip of lower incisors; V6, lower border of mandible to alveolus immediately behind 3rd molar tooth (posterior depth of mandible); V7, anterior limit of lower border of mandible to top of lower incisors (anterior depth of mandible); V8, opening of mouth; V9, distance from lower border of the body of the fourth cervical vertebra (C4) to the upper border of the body of C1; V10, distance from the spine of C1 to the occiput (atlanto-occipital gap); V11, depth of spine of C1; V12, distance between the spines of C1 and C2; V13, depth of spine of C2; V14, the angle subtended at the corniculate cartilages by lines drawn from the upper incisor and the lower incisor teeth (angle of vision); V15, length of perpendicular from lower incisors to LOV (the line of vision [LOV] is the line joining the upper incisor teeth and the corniculate cartilage); V16, the length of the perpendicular from the lower genial tubercle of the mandible to the LOV; V17, the distance from the upper incisors to the corniculate cartilages; V18, the length of the perpendicular from the most posterior part of the tongue to the LOV; V19, the antero-posterior thickness of the tongue and V20, V21 and V22 are the angles A, B and C of the triangle ABC. A is the most antero-inferior point of the upper central incisor tooth. C is the antero-inferior border of the body of the 6th cervical vertebra. B is the point of confluence of AB, the line along the occlusal surfaces of the maxillary teeth and CB, the line passing through the two points, C and the most anterior aspect of the body of the 1st cervical vertebra. Measurements 8, 14, 15, 16, 17, 18, 19, 20, 21 and 22 were made on head extension, all other measurements were made with the head erect.

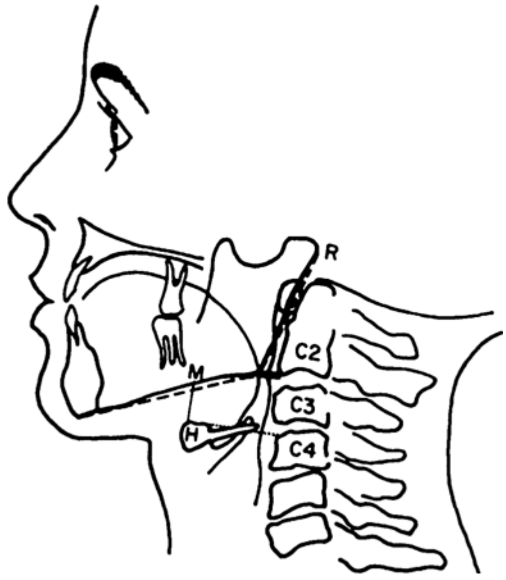

FIGURE 2 Diagram of normal lateral cervical X-ray film of a patient with head in neutral position. Mandibular angle was determined by drawing a horizontal (---) line from the intersection of two tangents of posterior ramus (R) and lower border of the mandible (M), across to the cervical (C2) spine. The position of the hyoid bone (H) was determined by drawing a horizontal line (---) from the upper margin of the hyoid bone to the adjacent cervical spine. The mandibulohyoid (MH) distance was measured from the upper margin of the hyoid bone (H) vertically upward to the lower margin of the mandible (M). Note that mandibular angle is situated at the lower C2 level, and H is situated between C3 and C4.

The posterior probability of group membership for each patient was used to compare the model prediction with the actual outcome. One patient was falsely predicted to have difficult laryngoscopy and intubation and another was falsely predicted to have easy laryngoscopy and intubation. This combined (clinical and radiological) model was associated with the same sensitivity (95.8% *vs* 95.4%) but with a greater specificity (96.9% *vs* 91.2%) and a greater positive predictive value (95.8% *vs* 87.5%) than with the clinical model alone. The negative predictive value of both models was similar (96.9%).

In both equations, the allocation rule assigned an individual to group 2 (i.e., laryngoscopy and intubation would be easy) if the numerical value (*l*) -after substitution in the above equations- was greater than zero and to group 1 (i.e., laryngoscopy and intubation would be difficult) if the numerical value (*l*) was less than zero (see Appendix).

With radiological criteria alone, discriminant analysis identified a single risk factor; V14, the angle subtended at the corniculate cartilages by lines drawn from the upper incisor and the lower incisor teeth (angle of vision) that had significant correlation with the prediction of difficult laryngoscopy and intubation. However, the sensitivity and the specificity with this predictor was poor (62.9.8% and 75.9%, respectively) compared with that noted with the above models.

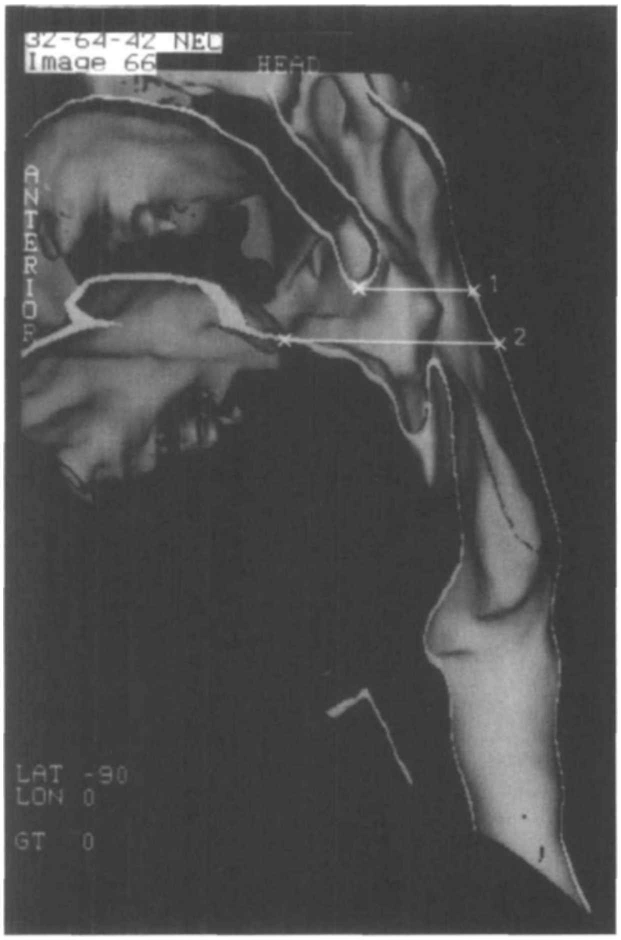

FIGURE 3 Points of various measurements from 3D-CT scans are shown. Various distances are: 1 = uvula to posterior pharyngeal wall, and 2 = base of tongue to the posterior pharyngeal wall.

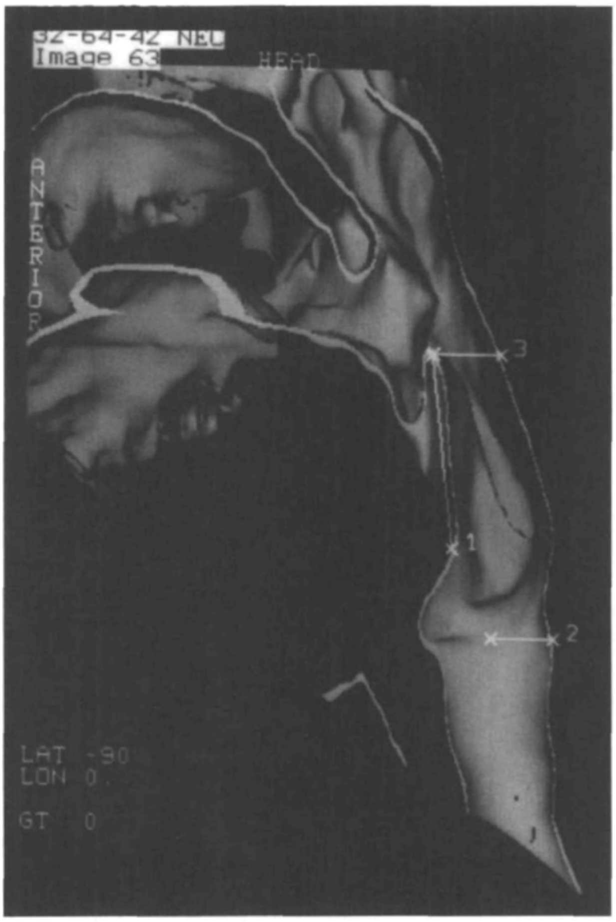

FIGURE 4 Points of various measurements from 3D-CT scans are shown. Various distances are: 1 = length of the epiglottis, 2= vocal cords to posterior pharyngeal wall, 3 = epiglottis to the posterior pharyngeal wall.

The receiver operating characteristic (ROC) plots and the area under the curve for the clinical and the combined models are shown in Figures 7 and 8. The typical curve will be convex and located above the "chance line". The area under the ROC curves, that measures the probability of the correct prediction of the clinical and the combined models, were found to be 0.933 and 0.973, respectively. This means that the clinical and combined models correctly predicated the actual outcome with a probability of 93.3% and 97.3%, respectively.

Discussion

This is the first study that used 3D-CT scans and combined all known clinical and radiological airway risk criteria in an attempt to identifying a working model for predicting difficult laryngoscopy and intubation. The multivariate discriminant analysis used in this study identified four clinical risk factors (thyrosternal distance, thyromental distance, neck circumference and Mallampati classification) that predicted difficult laryngoscopy and intubation. For the combined model (clinical and radiological), five risk factors [thyrosternal distance, thyromental distance, Mallampati classification, depth of spine C2 (V13) and angle A (V20; The most antero-inferior point of the upper central incisor tooth)] were identified as predictors of difficult laryngoscopy and intubation. Both clinical and combined models have the highest sensitivity (95.4 and 95.8%, respectively) and specificity (91.2 and 96.9%, respectively) ever reported.

In the most recently published study on clinical multivariate risk index,[21] the authors noted that their model falsely predicted difficult intubation in approx-

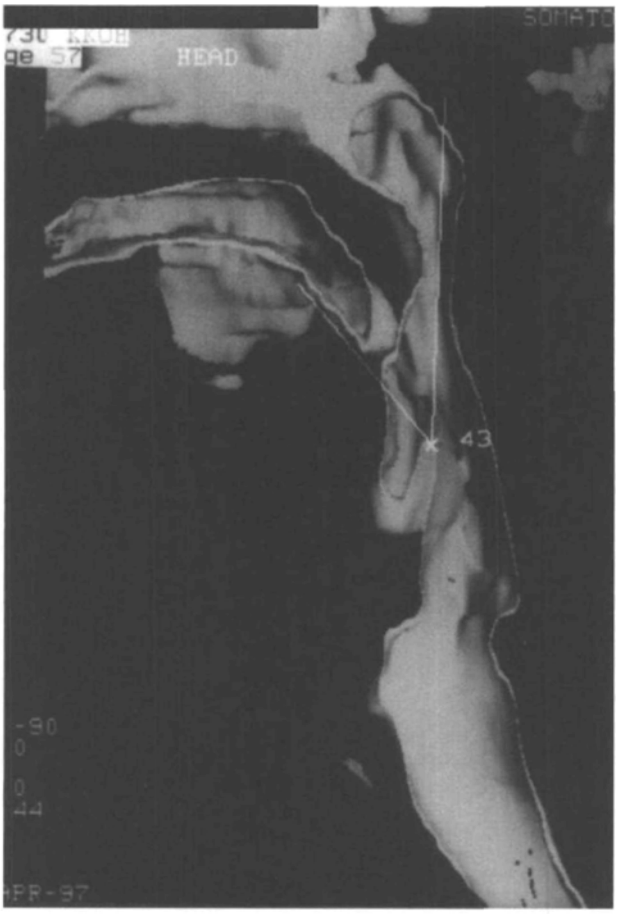

FIGURE 5 Points of measurements of different angles from 3D-CT scans showing the angle between epiglottis and tongue (43° in this patient).

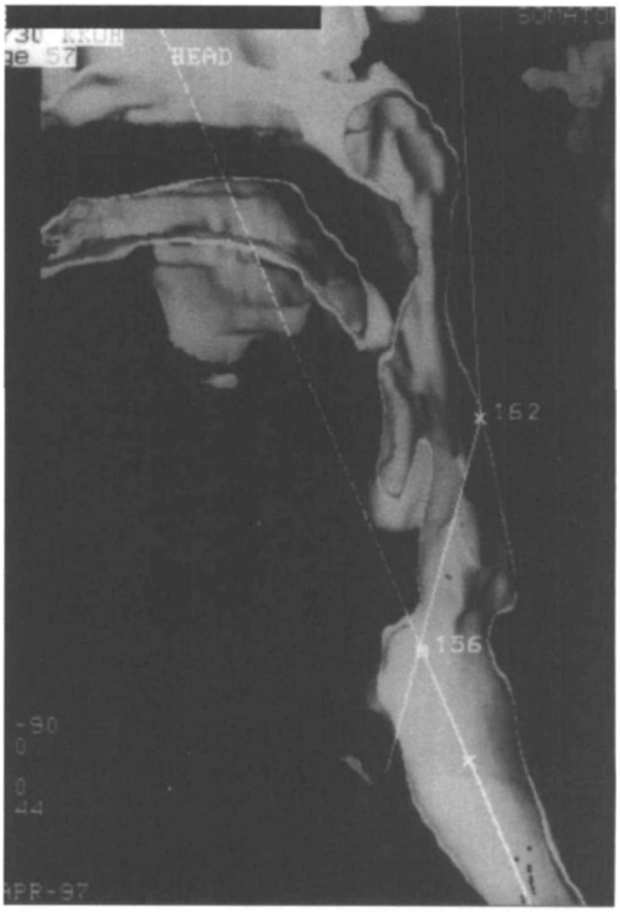

FIGURE 6 Points of measurements of different angles from 3D-CT scans. Various angles are between pharynx and larynx (162° in this patient), and larynx and trachea (156° in this patient).

imately two of three patients, or one of two patients. In another study of a multivariate risk index by El-Ganzouri *et al.*,[27] the sensitivity and specificity were reported to be 65% and 94%, respectively. The original data for Wilson risk sum[2] score yielded sensitivity of 75%, and specificity of 87.9%. However, when Oates *et al.*[3] evaluated the Wilson risk sum score in 675 cases, they reported a low sensitivity (42%) and high specificity (92%). Similar values (55.4% and 86.1%, respectively) were reported by Yamamoto *et al.*[28] The Mallampati score estimates the size of the base of the tongue to predict difficult intubation. However, it has been shown by several investigators that the Mallampati score is not sensitive enough for clinical practice.[3,18,28] Further, thyromental distance ≤7 cm, or sternomental distance ≤12.5 cm when used as predictors of difficult intubation had low sensitivity and specificity.[3,20] For this reason, in this study we evaluated both thyromental distance and thyrosternal distance separately. The sum of these measurements is equal to the sternomental distance.

The specific measurements derived from the 3D-CT scanning were similar to that described by Samra *et al.*[29] using NMR imaging. In agreement with Samra *et al.*,[29] we were unable to confirm the findings of White and Kander or that of Bellhouse and Doré.[13,16] White and Kander[13] studied some of the skeletal measurements included in this study. They reported that an increase in the anterior and posterior depth of mandible (V6 and V7 in Figure 1); a decrease in atlanto-occipital gap and C1-C2 gap (V10 and V12 in Figure 1); and limitation of movement at the temporomandibular joint were the factors that determined whether direct laryngoscopy would be easy or

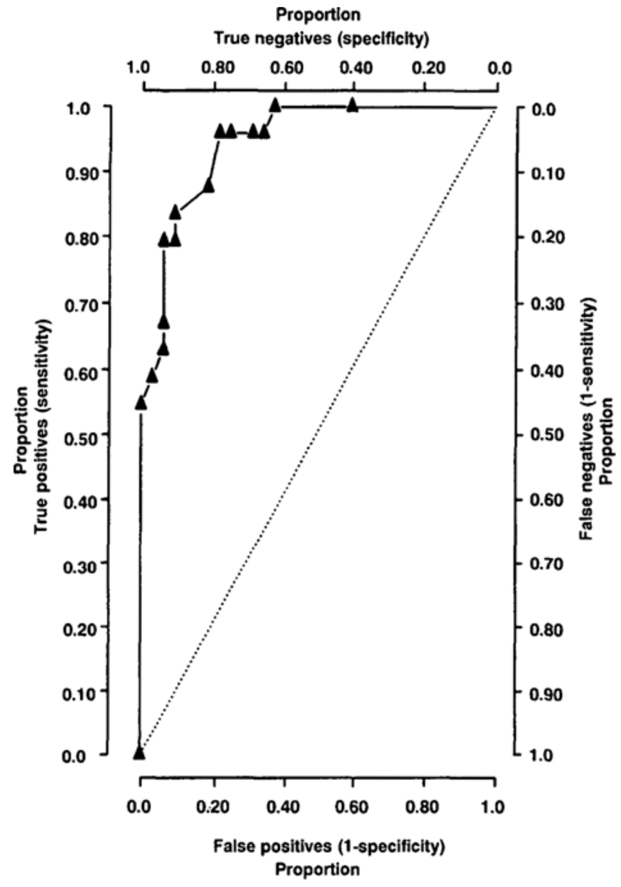

FIGURE 7 The receiver operating characteristic (ROC) of the clinical model. ROC curve is a graphic representation of the relationship between sensitivity and specificity of the model described. The dotted line indicates the 50% chance line of no accuracy in prediction or discrimination. The area under this ROC curve is 0.933 and it measures the probability of the correct risk rating. This indicates that our model correctly predicated the actual outcome with a probability of 93.3%.

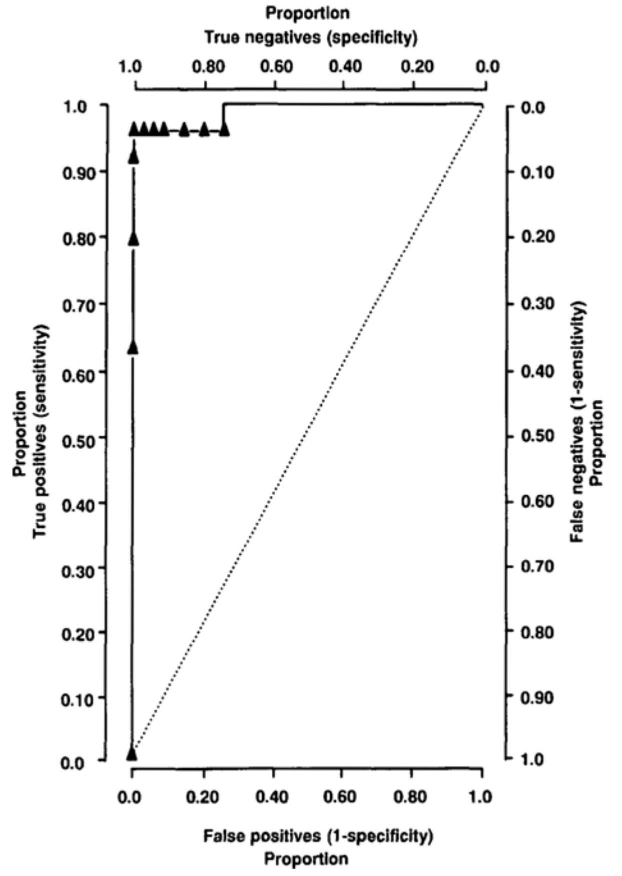

FIGURE 8 The receiver operating characteristic (ROC) of the combined (clinical and radiologic) model. The area under this ROC curve is 0.973 and it measures the probability of the correct risk rating. This indicates that our model correctly predicated the actual outcome with a probability of 97.3%.

difficult. In this study we could not establish evidence of relationship between difficulty in laryngoscopy and intubation and anterior and posterior depth of mandible or the atlantooccipital gap and C1-C2 gap. Similar observations have been reported by others.[14,16] This difference could be attributed to the fact that in the White and Kander[13] study assessment of the airway was carried out by otorhinolaryngologists using different techniques and instrumentation than that used by anesthetists for tracheal intubation.

It is notable that in this study and in that reported by Bellhouse and Doré,[16] the control groups were younger while patients, whose tracheas were difficult to intubate, were older. This is because controls were not matched for age in both studies. In this study and in that reported by Bellhouse and Doré,[16] univariate differences between the easy and difficult groups were noted in the following measurements: V14, V15, V21, V22 and in the ratio V14/V18 (Figure 1). In contrast, measurements V8, V17 were found to be significant in our study only, while measurements V9, V10, V16, V20 and ratio V16/V18, V16/V19 and V19/V18 were reported to be significant by Bellhouse and Doré.[16] Further, in the latter study (that was based only on different bony measurements by lateral radiographs), the discriminant analysis identified two measurements (V21 and ratio V16/V19) that predicted difficult intubation with a sensitivity of

77%. This is to be contrasted with the sensitivity reported with our models in this study. These differences could be attributed to several factors. First, we studied a larger number of patients (56 patients in this study *vs* 33 patients in Bellhouse and Doré study). Further, in contrast to the latter study, we used several clinical tests and 3D-CT scans for soft tissue measurements in this study.

In accordance with our results, Samra *et al.*[29] reported that soft tissue radiographs (measured from MRI scans) did not identify any measurable parameters that could categorically define the difference between unexpectedly difficult-to-intubate patients and control subjects. In this study, we evaluated all of the soft tissue measurements (from 3D- helical scans) that have been previously reported by Samra *et al.* [29]

The receiver operating characteristic (ROC) curve (Figures 7, 8) is a graphic representation of the relationship between sensitivity and specificity of our models. An important advantage of ROC analysis over traditional sensitivity and specificity analysis is that the area under the ROC curve is independent both of the cut-point criteria chosen and the prevalence of outcome of interest.[26] This independence allows comparison of the ROC area across study populations where sensitivity and specificity would be distorted by differences in the prevalence of outcome of interest across populations.[26] A model is considered perfect when the ROC area is 1.0, useless when it is <0.5 (that is under a line of no discrimination), has a low accuracy if between 0.5 and 0.7, and becomes useful with an area 0.7. The ROC areas observed in this study were high (0.933 and 0.973, respectively) indicating good discrimination with the models. This also implies reproducibility.

Several consultant anesthesiologists intubated the tracheas of patients in this study, but all intubating individuals were experienced at doing so and all obtained the best possible view. Therefore, we are confident that variation in the laryngoscopic grade due to the experience of the laryngoscopist was of minimal (if any) importance.

Helical scanning is a newly developed method that can scan a wide area of body quickly (30 sec) compared with a conventional CT scan.[30] Helical scan data are sequential, and a large number of tomographs can be reconstructed by interpolated algorithms. High-resolution 3D-CT images are drawn from those volume data. Once a three-dimensional image is available, the objects can be tilted, rotated, and cut freely and repeatedly.

Because of the diversity of factors involved, Wilson[31] concluded in his Editorial that no single test is likely to be perfect to predict difficult intubation. Similarly, Bainton[15] stated in his Editorial "The search for a "best test" should continue. I suspect it will rather be a "best algebraic sum" of several tests that will be the most satisfactory solution." This is what we established in this study. The use of the discriminant analysis, which calculates a linear combination between parameters, improved the predictive potential of our models.

This study demonstrated that methods of evaluation that involved combining different clinical (or clinical and radiological) criteria appeared to be sensitive in predicting difficult intubation. The models described in this study can be applied easily in clinical practice (see Appendix). The large ROC areas noted in this study imply reproducibility. These models are, however, not intended to be the absolute standards and further studies are needed for complete evaluation.

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Appendix

The clinical and combined (clinical and radiologic) models described in this paper are, respectively:

l = 4.9504+(thyrosternal distance x1.1003)+(Mallampati x -2.6076)+(thyromental distance x 0.9684)+(neck circumference x -0.3966) (1)

l =-10.2717+(thyrosternal distance x 1.2422)+(Mallampati x-3.368)+(thyromental distance x 0.966)+(depth of spine C2 x -0.3192)+(angle A x 0.176) (2)

In order to illustrate further how this model can be used clinically, two patients are presented who were assessed using these equations.

Case #1

A 27-yr-old man, 177 cm in height and weighing 81 kg was scheduled to undergo hemorrhoidectomy. On examination, the interincisor gap was 3.5 cm, the thyromental distance was 7 cm, thyrosternal distance was 8 cm, the Mallampati score was 2, and the neck circumference was 41 cm. He had a receding mandible (moderate) and the patient was able to protrude the lower incisors beyond the upper incisors. Wilson sum risk score was 1. Movement at the atlanto occipital joint was normal and the trachea was not deviated. No other medical history existed. Lateral x-ray disclosed that the depth of spine C2 was 24 mm and the angle A was 37°. This patient posed difficulty at laryngoscopy or intubation according to the criteria used in this study.

If we substitute the values of this patient into the clinical model (Equation 1):

l = 4.9504+(8 x 1.1003)+(2 x -2.6076)+
(7 x 0.9684)+(41 x -0.3966)
= -0.9442

If we substitute the values this patient into the combined model (Equation 2):

$$\begin{aligned} l &= -10.2717+(8 \times 1.2422)+(2 \times -3.368)+\\ &\quad(7 \times 0.966)+(24 \times -0.3192)+(37 \times 0.176)\\ &= -1.4569 \end{aligned}$$

Since the numerical values of the discriminant function (l) of both equations are less than 0, the both models correctly predicted that this patient would pose difficulty at laryngoscopy and intubation.

Case #2

A 49-yr-old woman, 157 cm in height and weighing 75 kg was scheduled to undergo laparoscopic cholecystectomy. On examination, the interincisor gap was 4 cm, the thyromental distance was 7 cm, thyrosternal distance was 8 cm, the Mallampati score was 2, and the neck circumference was 36 cm. She had a receding mandible (moderate) and the patient was not able to protrude the lower incisors beyond the upper incisors. Wilson sum risk score was 3. Movement at the atlanto occipital joint was normal and the trachea was not deviated. No other significant medical history existed. Lateral x-ray disclosed that the depth of spine C2 was 17 mm and the angle A was 20°. This patient posed difficulty at laryngoscopy and intubation according to the criteria used in this study.

If we substitute the values this patient into the clinical model (Equation 1):

$$\begin{aligned} l &= 4.9504+(8 \times 1.1003)+(2 \times -2.6076)+\\ &\quad(7 \times 0.9684)+(36 \times -0.3966)\\ &= 1.0388 \end{aligned}$$

Since the numerical value of the discriminant function (l) is greater than 0, the clinical model incorrectly predicted that this patient would pose no difficulty at laryngoscopy or intubation.

However, if we substitute the values of this patient into the combined model (Equation 2):

$$\begin{aligned} l &= -10.2717+(8 \times 1.2422)+(2 \times -3.368)+\\ &\quad(7 \times 0.966)+(17 \times -0.3192)+(20 \times 0.176)\\ &= -0.9828 \end{aligned}$$

Since the numerical value of the discriminant function (l) is less than 0, the combined model correctly predicted that this patient would pose difficulty at laryngoscopy and intubation. This example illustrates the greater predictive ability of the combined model as discussed in this paper.