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Static forces variation and pressure distribution in laryngoscopy performed by straight and curved blades

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Abstract- A theoretical analysis of the forces acting on the laryngoscope during the lifting of the epiglottis is carried out by applying the basic principles of statics.

The static model of a laryngoscope equipped with a straight and a curved blade and the forces variation, as a function of the introduction angle and of tissue reaction application point, are described. The pharyngeal tissues and epiglottis pressure distribution on the blade is obtained, with a 1mm^2 resolution, by measurements performed in-vitro on a simulation mannequin, using straight and curved blades.

The straight blade requires more effort than the curved one to obtain the same visualization of vocal cords, however forces exerted by using a laryngoscope with a curved blade do not vary linearly with the application point of tissue reaction. Average intensity of the tissue reaction has been found in the order of 32±11N. Pressure distribution is maximally concentrated on the tip of curved blades (0.5MPa on 5mm axial length), whereas it is more dispersed on straight blades (0.2MPa on 10mm axial length). The inclination of the handle also influences the effort of the operator: for both blades, from 0rad to 1.57rad, the lifting force shows a total variation of about 13% of the top value, the transversal forces vary less than 6% of the top value.

Keywords: laryngoscopy, pressure distribution measurement.

I. INTRODUCTION

THE laryngoscopy is a clinical procedure used during tracheal intubation, by which the vocal cords can be made visible through the glottis lifting. The laryngoscope is composed of a handle and a blade; the operator utilizes the laryngoscope blade to lift the tongue and other soft tissues in order to achieve the best view of the glottic opening. There are more than fifty blade types (various shapes, sizes and materials, re-usable or disposable) showing some differences that definitely change the intubation technique and effort [1], [2].

Many studies [3]-[11] have focused on force measurement in oro-tracheal intubation laryngoscopy. Bucx *et al.* measured the forces during laryngoscopy through a sensorized handle, considering also the maxillary incisor teeth lever [3], [4]. Mc Coy *et al.* measured the axial force exerted upon the handle [5]. Hastings *et al.* reported the time-dependent stress relaxation of the pharyngeal tissues during the intubation [6], [7]. Tissue pressure distribution measured by six miniature transducers has been reported in a recent in-vivo study [8].

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A realistic model of the upper airway's behaviour during laryngoscopy, although with limited experimental evidence, is also proposed [9].

However, most of the studies present in literature do not show how the forces exerted by the operator vary, in different blade types, along with the variation of the introduction angle and the position of tissue reaction application point. Moreover, in most cases, the pressure distribution exerted by soft tissues is unknown and the weight of the laryngoscope is not considered [6]-[11].

In the present study we describe the static model of a laryngoscope (equipped with a straight and a curved blade) including the weight: a simulation of the system's behaviour, as a function of the handle inclination and the position of the resultant application point, is carried out. We complete the model by introducing the experimental results of measurements conducted during in-vitro intubations (soft-tissue pressure distribution, intensity, inclination and application point of the resultant force acting upon the laryngoscope blade).

II. THEORETICAL BACKGROUND

We consider two laryngoscopes composed of the same handle and different blades: a straight and a curved one.

Fig. 1.A and 1.B represent the two laryngoscopes and the forces acting on them during laryngoscopy. We do not consider the third dimension because all forces act approximately on the same plane.

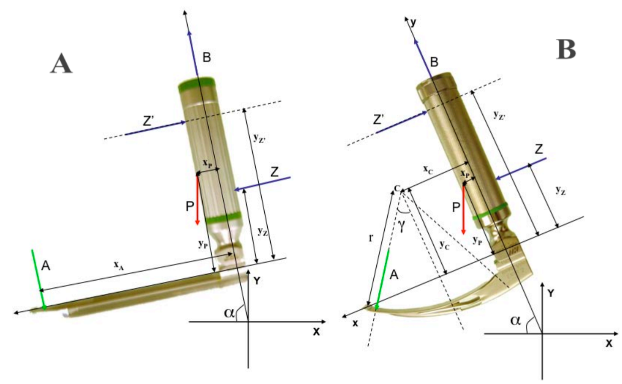

Fig. 1. Vectorial analysis of the laryngoscope with straight blade (A) and curved blade (B).

Two Cartesian Coordinate Systems are defined in the analysis (Fig.1): the first (xoy) is joint to the laryngoscope and the second (XOY) has a fixed point of reference. Angle α represents the inclination of the handle with respect to the horizontal axis. Forces acting on the laryngoscope at the end of the epiglottis lifting can be identified as follows:

- $\vec{B}$ handle coaxial force: it is exerted by the operator to raise the soft tissues.

• $\vec{A}$ force is exerted by tissues on the surface of the blade. We suppose this force perpendicular to the tangent plan in the application point by assuming the hypothesis of no-friction. The point of application will be determined from pressure distribution measurements.

• $\vec{Z}'$ and $\vec{Z}$ torque perpendicular to the handle: it is exerted, approximately, from forefinger ($\vec{Z}'$) and palm ($\vec{Z}$) of operator's hand in order to avoid a rotation of the laryngoscope during the manoeuvre. These are schematized as concentrated forces even though they are distributed upon the handle.

• $\vec{P}$ weight of the laryngoscope. It is applied in the centre of gravity.

The arms of the forces, with respect to a pole positioned in the centre 'o' of the xoy system, are introduced below:

• $\vec{y}_{Z'}$: arm of the force $\vec{Z}'$.

• $\vec{y}_Z$: arm of the force $\vec{Z}$.

• $\vec{x}_A$: arm of the force $\vec{A}$ acting on the straight blade.

• $\vec{r}_A$: arm of the force $\vec{A}$ acting on the curved blade.

• $\vec{r}_P$: arm of the force $\vec{P}$.

$\vec{B}$, having null arm, does not apply any momentum.

Introducing the static equations of the laryngoscope during the rising of glottis, the dependence of the forces on either angle (α) and force $\vec{A}$ application point, is studied. The reference pole for momentum calculation is 'o'.

The equations that regulate the equilibrium of the laryngoscope with straight blade (Fig. 1.A) are:

$$\begin{cases} B = A + P\sin\alpha \\ Z' = Z + P\cos\alpha \\ Z' y_{Z'} = Z y_Z + A x_A + \vec{r}_P \times \vec{P}. \end{cases} \quad (1)$$

By substituting $h = y_{Z'} - y_Z$ the equations (1) become:

$$\begin{cases} B = A + P\sin\alpha \\ Z' = \frac{1}{h}[A x_A - P(y_Z - y_p)\cos\alpha + x_p P\sin\alpha] \\ Z = \frac{1}{h}[A x_A - P(y_{Z'} - y_p)\cos\alpha + x_p P\sin\alpha]. \end{cases} \quad (2)$$

The curved blade is schematizable as an arc of circumference with its center C (x_c, y_c) and radius r (Fig. 1.B). The application point coordinates of force $\vec{A}$, expressed as a function of γ (the angle that $\vec{A}$ forms with the y axis), are:

$$x_A = r\sin\gamma + x_c \qquad y_A = y_C - r\cos\gamma \quad (3)$$

The arm (r_A) of the force is:

$$r_A = \sqrt{{x_A}^2 + {y_A}^2}. \quad (4)$$

It is useful to define the following relation:

$$l = \sqrt{r^2 + {x_C}^2 + {y_C}^2 + 2r(x_C\sin\gamma - y_C\cos\gamma)} \cdot \cos(\gamma + \operatorname{arctg} \frac{y_A}{x_A}). \quad (5)$$

By imposing the equilibrium of forces and torques, we obtain:

$$\begin{cases} B = P\sin\alpha + A\cos\gamma \\ Z' = Z + P\cos\alpha + A\sin\gamma \\ Z' y_{Z'} = Z y_Z + lA + \vec{r}_P \times \vec{P}. \end{cases} \quad (6)$$

Placing $h = y_{Z'} - y_Z$:

$$\begin{cases} B = P\sin\alpha + A\cos\gamma \\ Z' = \frac{1}{h}[lA - P(y_Z - y_p)\cos\alpha - A y_Z \sin\gamma + x_p P\sin\alpha] \\ Z = \frac{1}{h}[lA - P(y_{Z'} - y_p)\cos\alpha - A y_{Z'}\sin\gamma + x_p P\sin\alpha]. \end{cases} \quad (7)$$

h represents the width of the operator palm; it has been estimated to be, on average, approximately 7 cm. x_p and y_p have been experimentally determined. The position of centre C and the length of the bending radius (r) are directly measured on the curved blade: x_c=7.45cm; y_c=10.3cm; r=11.9cm.

The intensity of forces $\vec{B}$, $\vec{Z}'$ and $\vec{Z}$, exerted by the operator, are a function of their direction towards the fixed reference system XOY, i.e. the value of α, and of the position of application point of $\vec{A}$. We report, as an example, the graphs of Z obtained imposing the equilibrium of the laryngoscope with both blades in Fig. 2: $\vec{Z}$ intensity is reported as percentage of $\vec{A}$ intensity.

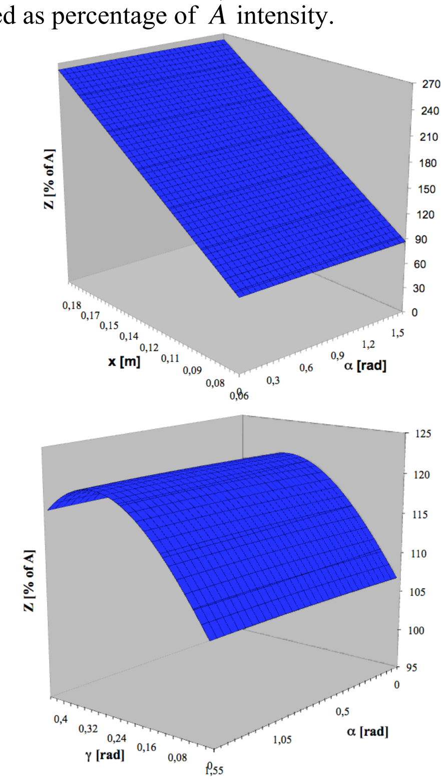

Fig. 2. Variation of Z as a function of the angle α and of the application point of A: straight blade on top and curved blade below.

As far as the straight blade is concerned, the intensity of Z is strictly dependent on x_A (arm of force $\vec{A}$): Z increases linearly, by the increase of x_A. This force is generated by the operator to balance the torque of $\vec{A}$; if the application point of $\vec{A}$ moves away from the handle, the momentum exerted by the tissue reaction increases. Thus, the nearer to the handle force $\vec{A}$, the lower the effort to lift the glottis: very short straight blades are recommended to be used with children.

As far as the curved blade is concerned, as the application point of $\vec{A}$ moves away from the handle, first Z increases, then it shows a reduction. Comparatively, the forces exerted by the operator on a laryngoscope with curved blade, are lower than those used with a straight blade.

Regarding both blades, the grip should be as close as possible to the upper extremity of the handle.

III. MATERIALS AND METHODS

Twenty intubations have been performed by an operator on a mannequin (Laerdal Airway Management Trainer) that reproduces, with good similarity [10], the upper airway soft-tissue mechanical properties of an adult human being, with both the straight blade and the curved one.

The laryngoscope handle has a cylindrical shape, a length of 15.2 cm, and a diameter of 3 cm. The main geometric and physical properties of the two blades are reported in Table I.

TABLE I BLADE PARAMETERS

	Curved blade	Straight blade
Internal length	11.2 cm	16.7 cm
External length	15.2 cm	19 cm
Width	3 cm	3 cm
Thickness	2.5 cm	2.5 cm
Barycenter	x_B = 1 cm; y_B = 8.4cm	x_B = 1.3 cm; y_B = 9.5 cm
Bend radius	11.9 cm	∞
Laryngoscope mass	428 g	404 g

Other laryngoscope designs and sizes could be considered by opportunely changing the values of the key parameters however, curved and straight blades are the most commonly utilized ones.

A pressure film transducer (Fuji Prescale Pressure film) is used to measure the pressure distribution applied by the tissues to the blade. Two pressure ranges are used:

• LLW film: range of 0.5-2.5 MPa and accuracy of 10%.

• LLLW film: range of 0.2-0.6 MPa and accuracy of 10%.

Ten intubations are made for each blade (five intubations using LLW film and five using LLLW film); the transducer is applied on the tip of the blade, on a rectangular region 35x14mm. The environmental thermohygrometric conditions and the duration of the intubations are: T=20°C, RH [%]=55%, t=5s.

Films change color during the intubations, depending on the pressure applied, and are then scanned and processed in order to transform the red optical densities into 256 grey-scaled levels. An experimental relation that converts the greyscale levels (L: reported in the matrixes) into optical densities (D: reported in ordinates of the graduation curves of the transducer) is obtained by data provided by the manufacturer: $D = 10\exp^{-0.02L}$. The images are elaborated by a LabView® based program, which generates a matrix with the mean greyscale level in every square millimeter of the image.

Four final matrixes (two for each blade) are then obtained with mean and standard deviation pressure values for every square millimeter of the image.

The barycenter position is determined experimentally. The laryngoscope is suspended by two points, in both cases a photo at the equilibrium position is taken. Two vertical lines through the suspension points are drawn on the photographs and the intersection point of the two lines determines the barycenter (B).

IV. RESULTS AND DISCUSSION

The results obtained by the more sensitive pressure films (LLLW) are reported for both blades in Fig. 3.

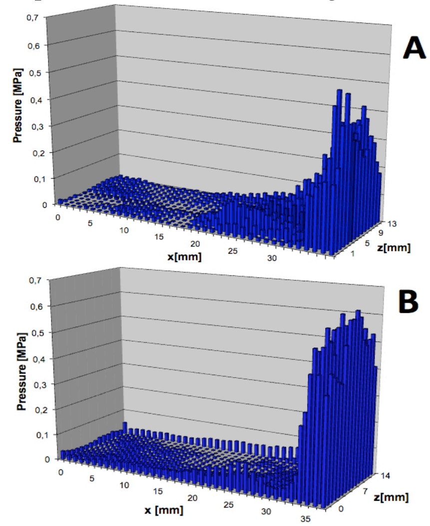

Fig. 3. Pressure distribution on the straight blade (A) and curved blade (B).

The curved blade concentrates the greatest part of the pressure upon the extreme part of the tip. Pressure measurement acting upon the whole curved blade is reported in [8], but there is no information about the concentration of pressure distribution. It must be noted that the tip of the blade has a bump that remains deeply in contact with the epiglottis during the rising.

The intensity of $\vec{A}$ and its application point are then calculable: the first by adding the contributions in force of each square millimeter of blade and the second by making a weighted mean of the pressures on the element position.

As far as the straight blade is concerned, the coordinates of the application point of $\vec{A}$ are: x_A=14.4 cm and y_A=0 cm. The intensity of $\vec{A}$ is 32±11 N ($p<0.05$) (Fig. 1.A).

As far as the curved blade is concerned, $\vec{A}$ is placed at 10.1 cm from O along the internal arc. This distance corresponds to an angle γ of 0.4 rad. The intensity of $\vec{A}$ is 32±6 N ($p<0.05$) (Fig. 1.B).

The values of $\vec{A}$, measured in both blades, are very close because the mechanical properties of the airways tissues do not change between the tests.

Although the analyzed studies are based on in-vivo intubations, a comparison with our results makes sense because the mechanical properties of the human pharyngeal soft tissues are well-reproduced by the Laerdal Airway Management Trainer: in [10] comparable mean forces, applied during intubations, were measured in-vivo and in-vitro.

Bucx *et al.* [3], [4] measured forces, on a curved blade laryngoscope, using a sensor positioned between the handle and the blade and a torque sensor. The mean values of the lifting force (F_s), of the force acting upon the maxillary incisors (F_m) and on the soft tissues (F_t) during the manoeuvre and the position of the tissue reaction were measured: F_s=8N, F_m=20N, F_t=28N and D=10.9cm from the handle axis. F_t has almost the same intensity and the same point of application as $\vec{A}$.

McCoy *et al.* [5] designed an *ad hoc* force transducer that did not alter the laryngoscope structure, shape, weight and was assembled in such a way to measure the whole tissue reaction: F=19±8 N. In this study, a curved blade was used and patients of different ages and weights were involved: this could justify the high variability of the measures of F and strengthen our result, obtained during intubations on an adult-shaped mannequin.

The intensities of $\vec{B}$, $\vec{Z}$ and $\vec{Z}'$, as a function of α are plotted introducing the experimental results in (2) and (7).

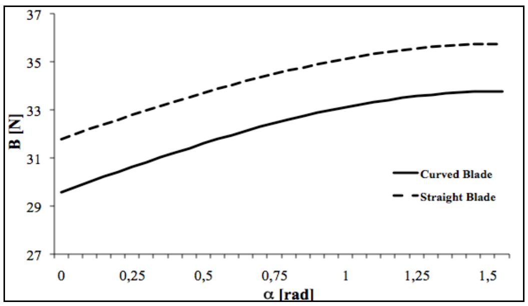

Fig. 4. Rising force B as a function of α.

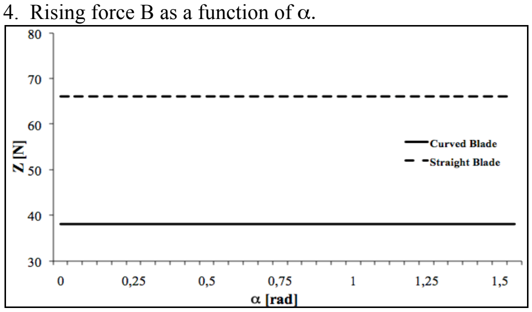

Fig. 5. Force Z, applied by the palm, as a function of α.

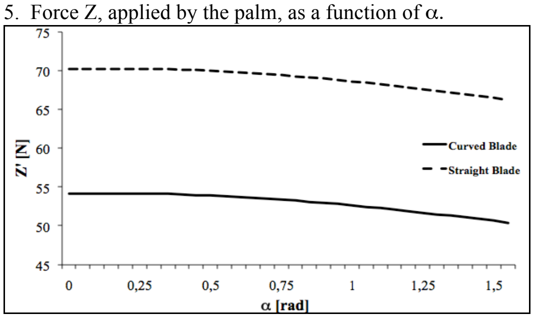

Fig. 6. Force Z' applied, by the forefinger, as a function of α.

Post hoc data evaluation shows that $\vec{B}$, $\vec{Z}$ and $\vec{Z}'$, for both types of blade, are not particularly influenced by the inclination of the handle.

Considering [4] we can notice that the sum of F_s and F_m is comparable with B. However Bucx *et al.* consider the teeth-lever as a help to the operator. In [3] the effect of the laryngoscope inclination on the lifting force measurement is quantified: as in our study this force varies of about 2.2N from 0 to 1.57 rad.

Although the two blades have a different shape, the force patterns are almost the same but the straight blade needs a higher effort, as also reported in [2], [11]. The transverse forces (Z and Z ') are higher than the axial force (B) for both blades. Thus, the greatest part of the user's effort is directed to balance the torque acting on the laryngoscope during the intubation. This is confirmed by Hastings *et al.* since they measured the lifting force, forces normal to the handle and torque acting on the handle obtaining the following results: F_L=38±2N, F_N=40±2N and T=4.3±0.2Nm [6], [7].

V. Conclusions

In this work neither the structure of the laryngoscope nor the intubation technique are altered and the pressure distribution along the laryngoscope blade is measured with a 1 mm^2 spatial resolution. In conclusion:

- The handle inclination only slightly influences the operator's effort during the intubation.
- The straight blade requires more effort than the curved one.
- Risks for patients (internal mucosa or upper airway damages) are higher using the curved blade than the straight blade because of the great pressure that the extreme part of the curved blade tip exerts upon the tissues.

An in-vivo trial would be useful to reinforce the results exposed above.

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