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Clinical paper

Automatic detection of oesophageal intubation based on ventilation pressure waveforms shows high sensitivity and specificity in patients with pulmonary disease



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ABSTRACT

Background: Unrecognised endotracheal tube misplacement in emergency intubations has a reported incidence of up to 17%. Current detection methods have many limitations restricting their reliability and availability in these circumstances.

There is therefore a clinical need for a device that is small enough to be practical in emergency situations and that can detect oesophageal intubation within seconds. In a first reported evaluation, we demonstrated an algorithm based on pressure waveform analysis, able to determine tube location with high reliability in healthy patients.

The aim of this study was to validate the specificity of the algorithm in patients with abnormal pulmonary compliance, and to demonstrate the reliability of a newly developed small device that incorporates the technology.

Materials and methods: Intubated patients with mild to moderate lung injury, admitted to intensive care were included in the study. The device was connected to the endotracheal tube, and three test ventilations were performed in each patient. All diagnostic data were recorded on PC for subsequent specificity/sensitivity analysis.

Results and discussion: A total of 105 ventilations in 35 patients with lung injury were analysed. With the threshold *D*-value of 0.1, the system showed a 100% sensitivity and specificity to diagnose tube location.

Conclusion: The algorithm retained its specificity in patients with decreased pulmonary compliance. We also demonstrated the feasibility to integrate sensors and diagnostic hardware in a small, portable handheld device for convenient use in emergency situations.

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Introduction

Unrecognised misplacement of the endotracheal tube (ETT) during endotracheal intubation and ventilation, has a reported incidence of 2.9–16.7% and is a frequent cause of morbidity and mortality in emergency intubations.^{1–3} In optimal conditions, such

as in the operation room during elective surgery, correct positioning of the tube is simple in most cases, and correct tube position can be ensured by using techniques aiming to improve tube placement (such as direct visualisation of the vocal cords) and by techniques to check the position of the tube after placement (such as observation of chest expansion, chest auscultation, capnography, spirometry or more advanced methods such as ultrasound⁴ or flexible bronchoscopy). Each of these methods has limitations and is often less reliable or even impractical in the emergency setting, and requires significant training for proper interpretation. Capnography with interpretation of the characteristic CO₂ waveform and the EtCO₂ value is currently the most reliable method to assess

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tracheal intubation, with a very high sensitivity and specificity both approaching 100%, although the specificity drops to 70–88% in patients with cardiac arrest.⁵ Moreover, during cardiopulmonary resuscitation many of these methods require interruption of chest compressions.^{6,7} In airborne emergency teams, weight constraints form an additional limitation.

During endotracheal intubation in an acute setting up to 17% of endotracheal tubes (ETTs) are positioned in the oesophagus, despite the performed checks,^{3,8} leading to a high risk of brain damage and eventually death. Chest auscultation is the most commonly used method to confirm ETT placement, but as mentioned it usually requires interruption of chest compressions during CPR.^{6,7} While quantitative waveform capnography is recommended as the standard for confirming correct ETT placement,⁹ well-known limitations of capnography in cardiac arrest victims exist however, as the capnography signal may be falsely low as a result of low cardiac output, low pulmonary flow, airway obstruction, or epinephrine use.^{10,11}

Consequently, in order to decrease the incidence of unrecognised oesophageal intubation, there is a need for a diagnostic device that is reliable, very easy to interpret, ultra-portable, economic and preferably integrable in existing devices, providing automatic immediate diagnosis after intubation from the first ventilation onwards. In addition such a device should involve minimal interruption of CPR, be independent of cardiac output, and practical in demanding out-of-hospital circumstances and suboptimal working conditions.

As shown and quantified in our previous research, the distinct difference in compliance and elastance between the trachea/lungs versus the oesophagus/stomach can be exploited to determine misplacement of the ETT. In a first study on two cohorts of 20 healthy patients enrolled for elective surgery, this method could discriminate between oesophageal and tracheal intubation with 100% sensitivity and 100% specificity,¹² after just one ventilation.

In the first reported evaluation,¹² our algorithm was assessed using pressure waveforms collected from patients with American Society of Anesthesiology (ASA) physical status I or II. This implies that the study population had healthy lungs with a normal compliance.

Because of the lower compliance of the lungs in many pathological conditions, and considering the physiological principle on which the algorithm is based, we anticipated that the algorithm might misdiagnose tracheal for oesophageal intubation, and consequently have a lower specificity in a patient population with decreased pulmonary compliance. Therefore, the aim of the study was to validate the specificity of the algorithm in patients with abnormal pulmonary compliance, admitted to an intensive care unit (ICU).

A secondary aim was to demonstrate the reliability of a newly developed small device that incorporates the technology and algorithm mentioned above. The hand-held device can be connected to an ETT and has integrated pressure sensors and electronics, enabling real-time analysis of the pressure waveforms and immediate alerts in the case of malpositioning of the endotracheal tube. For this research setting, the pressure waveforms are also transmitted through a Bluetooth connection to a laptop for data analysis and display of the waveform.

Methods

Study design and setting

The Ethics Committee of the University Medical Centre Groningen approved the study and waived the requirement for informed consent. A convenience sample of patients in the intensive care

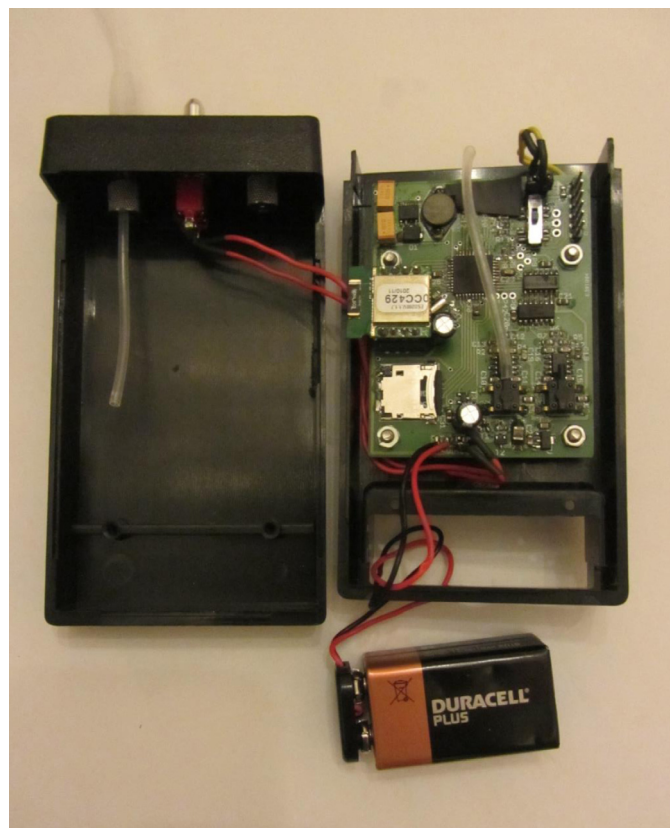


Fig. 1. Hand-held stand-alone diagnostic device.

unit was included. Inclusion criteria were controlled mechanical ventilation and at least mild to moderate lung injury with alveolar consolidation on chest radiography. To quantify the severity of the pulmonary disease, a Murray score was calculated for each patient.¹³ The Murray score is calculated based on alveolar consolidation on chest radiography, $\text{PaO}_2/\text{FiO}_2$ ratio, Positive End-Expiratory Pressure (PEEP) and lung compliance (Table 1). Exclusion criteria were: colonisation with multi-resistant bacteria, possible adverse effects on the patient (the decision was left to the treating physician of the ICU), pregnancy and age <18 years.

Study protocol and data collection

In the current study, only tracheal pressure waveforms were recorded. To record the waveforms, a connecting piece was attached to the in-site tube, as described previously.¹³ This connecting piece comprised one disposable thin air filled catheter (Vygon 71100.20 with an internal diameter of 1 mm) inserted through the tube lumen until 1 cm from the distal end, and a second catheter located at the proximal end of the tube. The catheters were connected with a luerlock to our custom-made battery-powered device containing two pressure transducers (Fig. 1). The device collected the pressure waveforms and determined tube location. Synchronously, the waveforms were sent to a laptop through a Bluetooth connection for subsequent real time and off-line data analysis.

After a patient was considered eligible for inclusion, haemodynamic stability and adequate oxygenation confirmed by pulse oximetry were assured before the measurement was performed. After assuring the patient had not been recruited for at least ten minutes, mechanical ventilation was stopped and the connecting piece was attached to the ETT and a self-inflating

Table 1
Murray score calculation table.¹³

Score	0	1	2	3	4
<i>Chest radiograph</i>					
Number of quadrants with alveolar consolidation	None	1	2	3	4
Hypoxaemia PaO ₂ /FiO ₂ (mmHg)	≥300	225–299	175–224	100–174	<100
PEEP (cm H ₂ O)	≥5	6–8	9–11	12–14	≥15
Lung compliance (ml/cm H ₂ O)	≥80	60–79	40–59	20–39	≤19

To calculate the Murray score: add individual scores for each category and then divide by the number of components used (not all patients have all measurements). PEEP = Positive End-Expiratory Pressure.

Σ versus E-Values

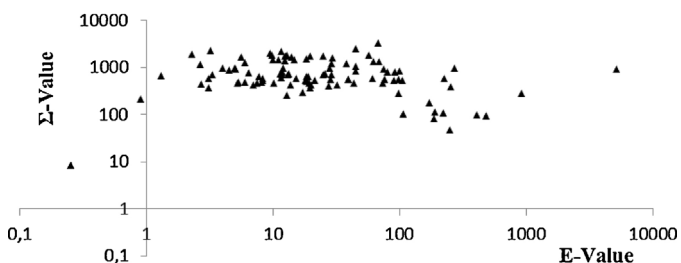


Fig. 2. Scatterplot of Σ -values versus E -values of the first three tracheal ventilations in all patients with pulmonary disease ($n = 35$). The dimension of the E -value is mmHg/sec; the dimension of the Σ -value is mmHg \times s/250.

ventilation bag (Intersurgical, Wokingham, UK). The patient was ventilated 3 times by a nurse experienced in resuscitation, and asked to ventilate at her discretion as if it were the first ventilations after endotracheal intubation. The pressure waveforms and metadata were collected on a laptop. Subsequently, the connecting piece was detached and the mechanical ventilator was reconnected and mechanical ventilation resumed. The fully automatic algorithm was used in the data analysis. This algorithm first performs an automatic ventilation detection, and secondly the algorithm calculates a measure of elastance (E -value) during the insufflation phase, and a measure of dynamic compliance (Σ -value) during the expiration phase on each identified ventilation cycle.

The calculated E -values and Σ -values are shown in Fig. 2. The specificity (ability to detect true tracheal intubation) of the algorithm was determined, when used in patients with pulmonary disease.

Results

During the inclusion period of 6 months, around 1000 patients were admitted at the intensive care department, of which 35 met the inclusion criteria. Mean (SD) age of the patients was 61 (15) years. Mean (SD) weight and height were 80 (18) kg and 173 (8) cm respectively, and 63% of patients were male. The mean (SD) body mass index was 27 (6) kg m⁻². The mean (SD) Murray score was 1.4 (0.6). The handheld device operated as expected, and generated D -values, in all patients in which it was used.

A total of 105 ventilations in 35 patients were analysed. Lung pathologies present in the included patients included pneumonia, atelectasis and traumatic lung injury. Fig. 2 shows the relationship between the E -values and Σ -values of the first three ventilations in each patient ($n = 35$).

The median (IQR, range) peak ventilation pressure during the test ventilations was 18 (13–25, 8–36) cm H₂O.

The median (IQR, range) D -value was 34 (14–99, 0.17–832). All these values were above the threshold value of 0.1.

Discussion

We have shown that the tracheal waveform analysis of pressure measurements at two different locations can reliably confirm tracheal ventilation with 100% specificity in patients with decreased pulmonary compliance. The result of the analysis can be reported as a single D -value reflecting differences of flow and elastance of both systems. This permits a straightforward verification by medical practitioners of correct intubation. Using our device, one test ventilation immediately after intubation provides an instant diagnosis of tube (mis)placement with a specificity of 100%, even in patients with pulmonary disease.

In order to achieve this high sensitivity, an analysis of the dynamic pressure patterns during insufflation, as well as during expiration is necessary. Relying on either E -values or Σ -values is not sufficiently accurate. As previously explained¹² and depicted in Fig. 3, during insufflation an E -value is calculated reflecting the elastance (pressure increase for a given volume increase). It can be thought of as the gradient of the tangent of the tracheal pressure curve at the moment of the highest pressure increase. Technically, the E -value is calculated as $E = (dP_{\text{dist}}/dt)/(\Delta P/\Delta x) \times P_{\text{dist}}$ at the moment of maximal increase in distal pressure (Fig. 3, γ) within a 300 ms timeframe, with dP_{dist}/dt being the rate of distal pressure increase; $\Delta P/\Delta x$ being the pressure difference between the distal and the proximal measurement in the ETT (and as such a measure of inspiratory flow); and P_{dist} being the distal pressure. The Σ -value can be conceived as the volume of air exhaled during expiration, visualised as the grey area in Fig. 3. Mathematically it is defined as $\Sigma = \int_{\alpha}^{\beta} [P_{\text{dist}} \times dt] - \int_{\alpha}^{\beta} [P_{\text{prox}} \times dt]$ expressed as mmHg \times s, but since technically the pressure values are discrete measurements at 250 Hz, it is calculated as $\Sigma = \sum_{\alpha}^{\beta} [P_{\text{dist}} - P_{\text{prox}}]$.

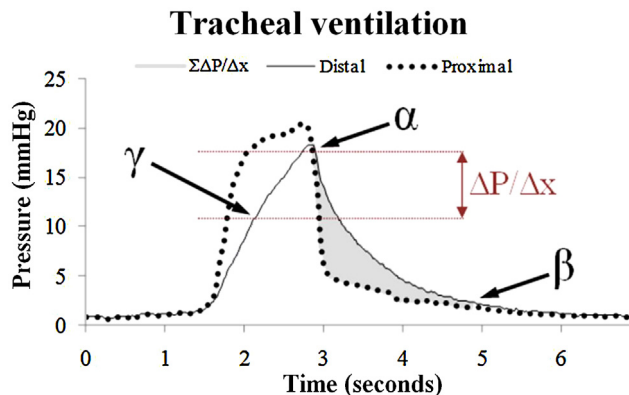


Fig. 3. Example of tracheal distal and proximal pressure waveforms. The E -value is calculated at the moment of maximal increase in distal pressure, and reflects the elastance at point γ . The Σ -value is the area between the distal and proximal pressure curve (α – β) during exhalation (grey area) and reflects a volume of exhaled air.

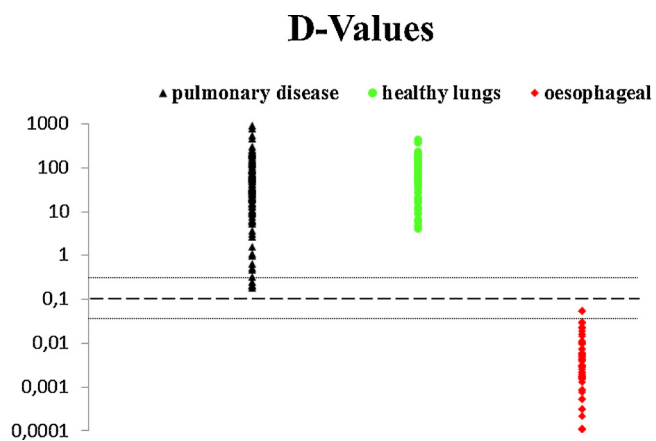


Fig. 4. *D*-values of the first three tracheal ventilations in all patients with pulmonary disease ($n = 35$), compared with the first three oesophageal and tracheal ventilations in elective patients (historical data)¹² without pulmonary morbidity. No data of oesophageal ventilations in ICU patients are available. The dotted line shows a threshold value of 0.1. The fine lines show threshold values of 0.05 and 0.5.

which is significantly less demanding for the CPU of the device. Consequently, \sum is expressed as $\text{mmHg} \times \text{s}/250$; E is expressed as $(\text{mmHg/s})/\text{mmHg} \times \text{mmHg}$, or mmHg/s .

In order to make the algorithm more predictable and computable, some substitutions of physiological variables by pressure values were performed: in determining elastance during inspiration, the flow was substituted by a pressure difference. Whereas the law of Hagen–Poiseuille describes the exact relationship between the pressure and flow, calculating the exact flow would unnecessarily complicate the computations, increasing the demand of the CPU, without improving the accuracy of the diagnosis, in particular since the variables in the Hagen–Poiseuille equation are either constant within one device (such as the diameter of the tube or the distance between measuring points), or not accurately known (such as the dynamic viscosity of the humid air, or the additional flow resistance due to the pressure catheter).

As such, from a physiological point of view, the E -value reflects the elastance of the lungs/oesophagus during insufflation, and therefore would in principle have as dimension mmHg/l ; the \sum -value reflects the volume of exhaled air, in principle having a dimension l . The D -value, being \sum/E would therefore have a dimension l^2/mmHg . For practical reasons however, no dimensions are used in the interpretation of the E -value, \sum -value or D -value.

Neither the E -value nor the \sum -value on their own, can yield a threshold value with an acceptably high sensitivity and specificity. Fig. 4 – also including the D -values of our previous study in healthy patients¹² – however demonstrates that the ratio of both values, labelled the D -value, gives a 100% sensitivity and specificity in all our patient recordings when a threshold value of 0.1 is respected, both in patients with normal lungs and in patients with decreased pulmonary compliance. Because of the moderate number of patients included in our studies however, we cannot exclude that in exceptional cases a false diagnosis may be made. Therefore, in a fully-automatic system, we may envisage that a green or red LED-light is activated in case of a D -value above 0.5 or below 0.05 respectively. Indicators of “moderate certainty” may be used for D -values between 0.1 and 0.5 (“probably tracheal intubation”), and for D -values between 0.05 and 0.1 (“probably oesophageal intubation”) respectively.

Because of the paramount importance of detecting oesophageal intubation, another approach may be to set the threshold D -value at 1, thereby increasing the sensitivity to detect oesophageal intubation in patients with reduced lung compliance.

This study has several limitations. First of all, only tracheal ventilation measurements were performed because oesophageal

intubation and insufflation was deemed inappropriate in fragile intensive-care patients. Still, however, the aim of the study was to investigate the accuracy of the algorithm in patients with pulmonary conditions, and therefore only tracheal ventilations were deemed sufficient. Further, elastance and discriminative values are likely to be similar for oesophageal intubation regardless of the presence or absence of lung pathology. Still, it is unknown what the oesophageal pressure readings would be in ICU patients. Among other factors, raised intra-abdominal pressure may influence the pressure patterns during oesophageal ventilation. It is therefore important to acknowledge that the accuracies described reflect the sensitivity to detect tracheal ventilation in patients with pulmonary disease, while no firm conclusions can be drawn on the sensitivity to detect oesophageal intubation in ICU patients in general. In addition, since only patients in ICU were included in the study, confirmation of the external validity in patients in emergency settings needs further research.

Secondly, the test ventilations to evaluate the diagnostic device were not performed in patients who were apnoeic or who had been resuscitated for several minutes. Nevertheless, the physiological conditions of the lungs in ventilated patients with normal tidal volumes which have not been recruited for at least ten minutes is the closest clinically feasible approximation of hypopnoeic patients in emergency situations. Since a recruitment manoeuvre in these patients is consistent with good clinical practice, it is appropriate to measure the pressure waveforms during such a recruitment manoeuvre.

Thirdly, only one type of ventilation device was used, and the manual ventilation manoeuvres may not have been identical to ventilations performed in a stressful emergency setting. The reported median (IQR) ventilation pressures of 18 (13–25) cm H_2O showed rather conventional ventilation pressures. In addition, because the algorithm is designed to compensate for differences in ventilation pressure, this should not significantly alter the calculated D -value.

Conclusion

Our previously published algorithm to detect oesophageal intubation retained its specificity in patients with decreased pulmonary compliance. We also demonstrated the feasibility to integrate sensors and diagnostic hardware in a small, portable hand-held device for convenient use in emergency situations. Further research will have to confirm our results in the out-of-hospital emergency setting.

Conflict of interest statement

A patent application (PCT/EP2009/066851) was filed.

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