3D imaging based web application for tracheal tube depth in preterm neonates.

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Running header: Tracheal tube depth application

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What's known on this subject

Correct depth insertion of a tracheal tube (TT) is challenging in preterm infants. Currently there is no reliable single-predictor model for neonates applicable to the whole range of size or age.

What this study Adds

We used 3D fetal images to measure mid-tracheal length, to help predict ideal tracheal tube insertion depth in preterm infants. Our best model is available as an easy to use internet application, using 4 clinical variables.

Contributors statement

Raksa Tupprasoot: Dr Tupprasoot helped co-design the study, performed the literature search, carried out the data analysis, and drafted the intial manuscript.

Dean Langan: Dr Langan performed the statistical analysis for the study, and critically reviewed the manuscript.

J Ciaran Hutchinson: Dr Hutchinson carried out the data analysis and critically reviewed the manuscript

Hannah Barrett: Dr Barrett carried out the data analysis and critically reviewed the manuscript.

Mike Sury: Dr Sury co-designed the study, performed the literature search, and critically reviewed the manuscript.

Owen Arthurs: Dr Arthurs co-designed the study, supervised the data collection, and critically reviewed the manuscript.

All authors have particpated sufficiently in this submission and take public responsibility for its content. All authors have approved the final version as submitted, and agree to be accountable for all apsects of the work.

Abbreviations:

PM MRI	post mortem magnetic resonance imaging
TT	Tracheal tube
TD	internal tracheal diameter
GA	gestational age
FL	foot length
CRL	crown-rump length
BW	body weight
3D	Three dimensional
Mid-TL	mid-tracheal length, defined as the distance between the lips and the mid tracheal point
uAL	upper airway length, defined as the distance from the lips to the glottis.
total	total airway length, defined as the distance from the lips to the carina
TL	tracheal length = totAL-uAL

Abstract

Background: Positioning a tracheal tube (TT) to the correct depth in pre-term infants is challenging. Currently there is no reliable single-predictor model for neonates applicable to the whole range of size or age.

Objective: In this study, we used post mortem magnetic resonance images from preterm infants to measure tracheal dimensions and to develop a clinical guide for TT positioning.

Methods: We measured tracheal length and diameter in a cohort of normal neonates and foetuses who underwent post mortem MRI (cause of death unexplained). The distance between the lips and the mid tracheal point (mid-tracheal length = mid-TL) and tracheal diameter (TD) was obtained. We produced univariate prediction models of mid-TL and TD, using gestational age (GA), foot length (FL), crown-rump length (CRL) and body weight (BW) as potential predictors, as well as multiple prediction models for mid-TL.

Results: Tracheal measurements were performed in 117 cases, with mean GA 28.8 w (range 14 to 42 w). The best linear relationship was between mid-TL and FL (mid-TL = FL * 0.914 + 1.859; R^2=0.94) but was improved by multivariate regression models. We developed a prediction tool using only gestation and body weight (R^2 =0.92) which is now available as a web-based application via the internet.

Conclusion: Post mortem imaging data provides estimates of TT insertion depth. Our prediction tool based on age and body weight can be used at the bedside and is ready to be tested in clinical practice.

Introduction

Correct depth insertion of a tracheal tube (TT) is essential to avoid misplacement into the bronchus or the pharynx, and this becomes more challenging as infant size decreases. Ideally, the TT tip should be placed at the mid-point between the larynx and the carina, and although its position can be checked by chest X-rays [1], repositioning is frequently necessary [2].

Methods used to investigate the correct or ideal TT depth have involved either imaging with conventional chest radiographs or post mortem (PM) autopsy [3 – 6] and several formulae or rules have been published to help accurate predict safe insertion depth. Studies have shown that airway length and tube insertion depth have linear relationships with body weight [7], gestation[8], foot length [9], and body size such as crown-rump [10] or crown-heel lengths [4, 10]. The European Resuscitation Council has recommended that the TT depth estimation should be based on gestation [11] although in practice, the difference between body weight and gestation may not be appreciable [12]. However, most of the published studies have involved too few very (<32-28 w) or extremely preterm (<28w) infants and relationships change or become non-linear when infants less than 1 kg are included [8, 13, 14]. Currently there is no reliable single-predictor model for neonates applicable to the whole range of size or age.

Modern three dimensional (3D) cross-sectional imaging can be used to measure airway and tracheal dimensions and should be more accurate than simple 2D chest radiography. 3D imaging of airway structures is only rarely indicated in live preterm infants, but recently PM magnetic resonace imaging (PMMRI) is being used routinely to investigate the cause of death

[15]. Our institutional autopsy imaging database provides 3D data on the airway dimensions in a wide range of fetuses and neonates and could prove useful to develop a mathematical model for the bedside. Furthermore our database includes fetuses younger than 22w gestation who although being too preterm to survive, may be of future interest.

The aim of this study was to use 3D detailed anatomy derived from fetal PMMRI to measure airway parameters, and to develop a bedside mathematical tool to predict optimal TT insertion depth.

Methods

Recruitment and criteria

We evaluated PMMRI of all fetuses (miscarriages and stillbirths) aged less than 44 weeks gestation referred to our institution from February 2012 to September 2015. Ethical approval was obtained for analysis of PMMRI and written informed consent was obtained from parents. Bodies were stored in a mortuary at 4°C until PMMRI. Cases were excluded if the airway was abnormal on either PMMRI or subsequent autopsy, or where image quality was inadequate to permit measurements. Demographic data acquired from the clinical notes included gestational age (GA; weeks), body weight (BW; kg), foot length (FL; cm), and crown-rump length (CRL; cm).

Magnetic Resonance Imaging

Imaging was performed on a 1.5 T scanner (Avanto, Siemens Medical Solutions, Erlangen, Germany) with a conventional phased array head coil. Conventional 3D T_1-weighted and T_2-weighted sequences were examined by a pediatric radiologist for clinical purposes [16]. T_2 weighted isotropic sequences of the head and chest were used to create 3D multi-planar (sagittal, coronal and axial) datasets.

Tracheal measurements

Reformatted images (Figure 1), using a Centricity Web DX Viewer (Centricity WebPACS system, 2006; GE Healthcare, Chalfont St Giles, UK) were used to measure and calculate the following:

1. upper airway length (uAL) = distance from lips to glottis. The position of the glottis was defined that part of the airway at the level of C5/C6 intervertebral disc space because this has a close relationship with the cricoid cartilage;
2. total airway length (totAL) = distance from the lips to carina;
3. tracheal length (TL) = totAL-uAL;
4. the mid-tracheal length (mid-TL) = the distance between the lips and the mid-tracheal point, and calculated as uAL+ ½TL; this is equivalent to a tracheal tube depth
5. internal luminal tracheal diameter (TD) measured at the mid-tracheal point.

All measurements were made to the nearest mm by a single observer (RS). Twenty datasets were selected at random and measurements were repeated by a second observer, (OJA), to assess inter-observer variability.

Statistical analysis

Univariate linear regression models were fitted for both outcome variables (mid-TL and TD) using 4 predictors (GA, BW, FL and CRL). Two multivariate regression models were fitted for mid-TL using (1) the two most readily available predictors (GA and BW and (2) all four predictors. These prediction models were developed into a web application to for clinical practice. For each regression model, subjects were identified in whom the model would have predicted a mid-TL that would have resulted in a TT inserted either too short or too long (i.e. the TT tip would be above the glottis or below the carina). Bland-Altman limits of agreement were calculated to describe inter-observer variability of mid-TL and, using a regression approach [17], to account for a relationship between variability and the mid-TL itself. All analyses were carried out in R (version 3.3.0).

Results

Tracheal measurements were performed in 117 fetuses (mean GA 28.8 w, range 14 to 42 w; 17 fetuses were below 22 w, Table 1). The smallest infant weighed only 50g, and had a CRL of 10cm. Mid-TL ranged between 2.8 and 10.8cm (Table 1).

All predictor variables had a strong linear relationship with mid-TL. FL had the highest adjusted R^2 of 0.94 (Table 2) and produced the fewest predictions of tracheal tube tip positioning below the carina 3 (2.6%) or above the glottis 2 (1.7%; Table 2 & Figure 2). BW had the lowest adjusted R^2 of 0.86 but our results suggested that this may be because of a non-linear relationship, particularly at low birth weights (log transformation R^2 0.91; Figure 2). The multivariate regression model using all four predictors had only a marginally better fit than the multivariate model with only GA and BW (adjusted R^2 0.94 and 0.92 respectively; Table 3).

Formulae for these models were made accessible through a web-based application (https://chpredict.shinyapps.io/shinyapp/ ; Figure 3).

TD was only measurable in 58 (50%) of fetuses. Univariate prediction models for TD all had adjusted R^2 = 0.51 to 0.53 and multivariate regression modelling was not undertaken.

Variability (agreement between observers) of mid-TL increased as mid-TL increased: 95% limits of agreement were ±0.25cm and ±0.75cm for mid-TL 4cm and 10cm respectively.

Discussion

We used fetal PMMRI 3D images to measure mid-tracheal length, in order to produce a mathematical model to help predict the ideal tracheal tube insertion depth in preterm infants. Our best model to predict mid-TL uses 4 clinical variables, but a model using only GA and BW was almost as good. Tracheal diameter was not easily or accurately measured due to small size.

Other investigators have used PM fetuses and neonates to measure ideal TT insertion depth. Embleton and colleagues (2001) dissected 39 specimens ranging from 24 to 43 weeks post-menstrual age and showed that FL was a much better predictor of TT depth ($R^2 = 0.79$) compared to BW ($R^2 = 0.67$) and age ($R^2 = 0.58$) [9]. Neonatal body dimensions however, such as foot length and crown rump length, are neither routinely measured at birth nor readily achievable in an emergency intubation setting. A prediction model combining body dimensions with BW and GA may be more slightly more accurate but is less practical in a clinical situation than a model using GA and BW alone.

Previous studies in live infants have developed formulae based on age and weight. The 7-8-9 rule used BW to estimate TT insertion depth defined as the distance from the lips to the level of the first or second thoracic vertebra on a chest radiograph [7]. The derived formula was length = 1.17 x BW + 5.58, which approximates to 6 + each kg body weight: this produces a TT depth of 7 cm for 1 kg, 8 cm for 2 kg and 9 cm for 3 kg infants. The data in this study from infants <1kg however were sparse, and Peterson and colleagues reported that the formula gave TT depths that were too long in preterm infants <750g [13]. An internet tool (currently available at http://www.nicutools.org/) uses the formula TT depth (cm) = 1.1 x BW + 6.1, but only for infants >1 kg: for smaller infants the TT depth is 5.5 cm if <500g, 6 cm if 550 to 700g and 6.5 cm if 700 to 999 g. Kempley and colleagues reported that TT depth was not linearly related to BW and that estimates based on GA reduced the need for TT repositioning [8]. We found also that GA was not linearly related to mid-TL especially in our smallest fetuses.

Nevertheless, a clinical study randomising neonates to receive a TT depth based on either GA or BW suggested that there was no appreciable difference [12] and that neither predictor was reliable at achieving satisfactory positioning: BW (the 7-8-9 rule) was successful in only 25 of 49 (51%) infants and GA was successful in 16 of 41 (39%) [18].

In light of these findings, our data and model may help to better predict the TT depth. Firstly, our data is based on 3D anatomy of tracheal and airway measurements from MR imaging, rather than two dimensional radiographic imaging using vertebral body heights as reference levels for the trachea. Secondly, we provide new high quality data in the <22 week group which increases the confidence in the mathematical model to predict mid-TL for potentially viable infants of 23 to 25 week GA. Thirdly, our data supports the clinical findings of others that any single predictor of TT depth is not as reliable as a combination of predictors. Fourthly, by incorporating all our data, we have made available a web-based application, which may be useful at the bedside. Whether using the data in this study improves ETT placement accuracy remains to be determined in the appropriate clinical setting.

The main limitation of our study is that we did not measure the effect of the position of the head and neck. Neck extension is known to lengthen the trachea [19 - 21] and imaging in a defined neutral position would provide the most reliable predictions. There are physiological changes which occur after death which may mean that our measurements will be different to those in live infants. The trachea may be shorter at PM because the diaphragm applies less traction [22] and therefore our formula may under-estimate mid-TL and TT insertion depth for live infants. Collapse of the upper airway in a dead infant may account for a small degree of measurement error and was most evident when we attempted to measure TD. Nevertheless inter-observer variation was small and our measurements were repeatable. Our TT insertion depths were also made to the nearest mm but clinicians may not be able to achieve accuracy of insertion depth more than to the nearest 0.5cm; we recommend rounding up or down appropriately. We look forward to testing our formula in clinical practice and potentially improving it with additional PM imaging and clinical data.

Conclusion

PM imaging data provides reproducible anatomical measures of tracheal length in order to predict ideal tracheal tube insertion depth. We have provided an easy to use internet application which may be used at the bedside to improve TT tube placement. This tool remains to be validated in clinical practice.

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Table legends

Table 1.

Summary of demographic details.

midTL = uAL + ½ (totAL-uAL)

Table 2.

Univariate linear models of mid-TL

Table 3.

Multivariate linear models of mid-TL

Figure legends

Figure 1: Airway measurements

Example of multi-planar reconstruction (MPR) of PMMR sequence and tracheal measurements – from mouth to carina (left and centre, top & bottom row), mouth to epiglottis (right, top and bottom row)

Figure 2. Relationship between mid-TL and GA

Scatter plots of mid-TL against the four predictor variables; GA (top-left), FL (top-right), CRL (bottom-left) and PMW (bottom-right). Regression lines (from table 2) are plotted in red. Vertical lines represent absolute tracheal length (TL) in each case, and those in red represent where predicted mid-TL falls outside this range.

Figure 3. Screenshot of web-based application

Formulae for both multiple prediction models of airway to mid tracheal length are currently accessible through a web-based application situated at https://chpredict.shinyapps.io/shinyapp/