Printed three-dimensional airway model assists planning of single-lung ventilation in a small child

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Abstract

Background: Single-lung ventilation in infants and small children is challenging because suitable sizes of double-lumen cuffed tracheal tubes are not available. A 6-yr-old child required pulmonary saline washout for primary alveolar proteinosis, and therefore needed sequential single-lung ventilation in order to achieve safe oxygenation. Before undertaking this potentially hazardous procedure, we practised bronchial intubation on an anatomical model of her airway constructed from computed tomography (CT) data.

Methods: We created a full-scale, anatomically accurate, transparent plastic model of the trachea and main bronchi on a three-dimensional printer using data from a CT scan. We then performed several different airway approaches to identify those likely to be most suitable, ex vivo, before the clinical procedure was carried out on the patient.

Results: The model helped us to choose the type and size of bronchial tubes and to practise their insertion beforehand. Subsequently, during anaesthesia, the chosen technique was successful.

Conclusions: Three-dimensional printing of a model of the airway of a small child aided planning of bronchial intubation and single-lung ventilation. Three-dimensional printing of airway structures may have wider application in anaesthesia practice.

Key words: airway management; models, anatomical; one-lung ventilation

For thoracic surgery in adults, single-lung ventilation can be achieved readily using a double-lumen tube to intubate the trachea and a bronchus. This approach is not feasible in infants and small children because the smallest cuffed double-lumen tube available is 26 French gauge (Ch.) [French gauge (also known as Ch.) is a system used to describe the size of a catheter; external diameter in millimetres=Ch./3], which is too large and not recommended for children <8 yr old.1

Single-lung ventilation in infants and small children is usually achieved by insertion of a single-lumen tube into a bronchus because, typically, only one lung needs to be ventilated while the other lung undergoes a surgical procedure.2 3 To facilitate

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whole-lung lavage, both lungs need to be ventilated, sequentially, and therefore alternative techniques are required when a child is too small for a cuffed double-lumen tube. The use of two individual cuffed tubes alongside one another is a recognized technique in children. Either one tube is placed in a bronchus and the other in the trachea, or both main bronchi will need to be intubated. With both arrangements, it can be challenging to position the tubes correctly. Wide-bore tubes may cause mucosal damage, and narrow tubes may not be long enough to pass endobronchially.

A conventional single-lumen tube can be guided into a bronchus by direct (bronchoscopy) or indirect visualization (X-rays), but choosing the correct size and length of the tubes is crucial. Normal ranges of airway lumen dimensions in children, according to age group, can be estimated from autopsy and computed tomography (CT) data, but because there is variation between patients, knowledge of the precise dimensions for an individual patient should be more useful.

Here, we report the use of an individualized three-dimensional (3D) printed model of a small child’s airway, derived from CT data, to practise and optimize bronchial intubation techniques. These techniques were then successfully performed on the patient to facilitate lung lavage.

Methods

The patient

A child aged 6 yr (14.7 kg, height 104 cm, <1st centile for both weight and height), with pulmonary alveolar proteinosis, required anaesthesia for whole-lung lavage. Previously, for the same procedure when the child was aged 5 yr, single-lung ventilation had been achieved by using single-lumen bronchial tubes. Severe oxygen desaturation occurred during the tube placement. This may have been prevented or minimized by precise knowledge of the child’s tracheobronchial anatomy beforehand.

Thoracic computed tomography

A conventional multislice computed tomograph of the chest on a 64-slice multidetector system was obtained (Siemens SOMATOM Definition; Siemens Healthcare, Erlangen, Germany; Fig. 1). Images were reconstructed with a soft tissue algorithm and viewed on standard soft tissue, lung, and bone window settings. Further 3D reconstruction was performed on Osirix (open source code; http://www.osirix-viewer.com (accessed 17 August 2015)).

Three-dimensional printed model

Computed tomographic images were imported in the postprocessing software Mimics (Materialise, Leuven, Belgium). A virtual 3D reconstruction of the patient’s airways was performed using an established technique, including the trachea from the larynx level and the main bronchi up to the first bronchial bifurcation. The model was scaled in 3D by a factor of 1.15 to account for the patient’s growth between the time of CT investigation and the day of the intervention according to standard growth charts. The airways lumen was printed in clear and rigid resin (Somos Watershed XC; DSM Somos, Elgin, IL, USA) using an SLA Viper machine (3D Systems; Rock Hill, SC, USA; Fig. 1).

Dimensions of the model were measured with callipers (Mitutoyo Absolute IP66; Mitutoyo Corporation, Sakado 1-Chrome, Kanagawa, Japan).

Intubating the model

The model allowed experimentation with various sizes of tracheal tubes (Figs 2–4). Unless otherwise stated, all tubes tested on the model were Microcuff® (Halyard Health Global Headquarters, Roswell, GA, USA), and sizes were the internal diameter in millimetres.

Editor’s key points

- Three-dimensional (3D) printers make 3D objects by laying down successive layers of material.
- They are widely used in industry, and are increasingly being used for medical applications.
- The authors faced difficulties planning airway management of a child requiring single-lung ventilation.
- A 3D printed model of the trachea and main bronchi was successfully used for planning and preparation.
The following tracheal tubes were used: 3.5, 4.0, and 4.5 mm Microcuff® tracheal tubes, 3.0 mm extra-long Portex tracheal tube (Smiths Medical, St Paul, MN, USA), and left 26 Ch. double-lumen tube (Rüsch Bronchopart®, Duluth, GA, USA).

External diameters of the tubes were measured with callipers (as above). All measurements were repeated three times, and the stated value is the mean to the nearest 0.1 mm.

Intubating the patient

Conventional digital radiography was used to confirm positioning of tracheal and bronchial tubes before the lung lavage, using a universal biplane C-arm angiography system (Siemens AXIOM Artis BA eco; Siemens Healthcare, Erlangen, Germany). Iodinated contrast material was used in the form of Omnipaque 300 (Iopamidol; Bracco UK Ltd, High Wycombe, UK) to instil into the cuffed tubes for X-ray identification.

Results

Intubating the model

In the week before the lung lavage, use of the model allowed us to identify two potential issues with bronchial intubation (Fig. 1). First, the narrowest part of the model was at the cricoid region. At this site, the cross-section was oval, so that the internal diameter was minimal in the coronal plane (7.4 mm) and maximal in the sagittal plane (11 mm). The maximal diameter of the Rüsch Bronchopart® Ch. 26 tube was at the rim of the tracheal cuff (at least 9.2 mm), which was too wide to pass through the cricoid region of the model. Two single-lumen tubes would therefore need to be used, with their combined outside diameters <11 mm to pass through the cricoid region. A simple test of size compatibility was to insert the tubes into the model, and by doing so, compression of the tubes could be taken into consideration.

The second issue related to lengths. The required total length of a bronchial tube could not be determined from the model because the pharynx and mouth were not included and, furthermore, the distance from lip to carina is known to change with extension and flexion of the head and neck. We estimated that...
a tube placed in the mid-trachea would need to be 15–17 cm long and, using the model dimensions, estimated that a bronchial tube would need to be ~4 cm longer. In addition, the model identified that the right upper lobe bronchus branched from a short right main bronchus (length 8 mm), which could make positioning a tube in the right main bronchus difficult (Fig. 1); this was not initially appreciated on the CT images (Fig. 1).

We established that placing a size 4 tube into either bronchus and a size 3.5 tube into the trachea was feasible (Figs 2 and 3). The combined diameter of these tubes was 10.6 mm, but including the rim of the deflated cuffs in the measurement was 10.8 mm. By testing these tubes directly on the model, we identified that the bronchial tube was easier to fit when placed first and in a posterior position at the cricoid region; the tracheal tube was then placed anterior to it.

We were concerned that the size 4 tube might not be long enough to pass endobronchially in the patient and therefore practised an alternative technique using both a size 4.5 tube and a size 3 extra-long uncuffed tracheal tube (known as a ‘croup tube’, which is a long tracheal tube used to intubate children with airway inflammation; Fig. 4).

Intubating the patient

On the day of the whole-lung lavage, once anaesthesia had been established, the size 4 tube was inserted into the trachea to achieve bilateral lung expansion and maximal oxygenation. It was then advanced into the left bronchus and the cuff inflated. Insertion of the size 3.5 tube through the vocal cords, anterior to the size 4 tube, was aided by the use of a bougie. The cuffs were inflated slowly with air with minimal volumes, until satisfactory single-lung ventilation was obtained. The tube cuffs were injected with a small volume of iodinated contrast material, and radiographically showed satisfactory tube placement (Fig. 3).

The left lung lavage began via the bronchial tube. Towards the end of lavaging the left lung, the tube migrated out of the left bronchus into the trachea, probably because it was not long enough. The tubes were removed and a size 3 ‘croup’ tube was placed into the left bronchus followed by a size 4.5 into the short right main bronchus: the cuff remained, in part, within the trachea to ensure that the right upper lobe bronchus was not obstructed by it, which was confirmed radiographically (Fig. 4). Right lung lavage then proceeded.

At the end of the procedure, the bronchial tubes were removed and a size 5 tracheal tube was inserted. The patient was ventilated overnight, extubated successfully the next day, and made an uneventful recovery.

Discussion

We have shown that a 3D printed anatomical model derived from CT data helped to plan and practise bronchial intubation in a child in whom single-lung ventilation was going to be challenging. The transparent plastic model enabled us to practise several bronchial and tracheal intubation approaches and tube combinations in order to refine our technique before anaesthesia. This type of imaging-based modelling could be applied to other challenging airway situations where the opportunity to practise ex vivo and their use as a teaching aid may be valuable. Alternative ‘hi-tec’ solutions would include development of high-quality 3D imaging and the use of haptic simulators (virtual airway management).

Creating physical 3D prototypes from computer models is used widely in industry. In medicine, models can evaluate complex and unusual anatomical structures that are not easily understood in two dimensions. Models have been used in neurosurgery, orthopaedics, and more recently, to evaluate heart valves. For airway problems, models have helped to manage an adult with relapsing polychondritis and to create a model of a stent for use in a child.

Our model had several useful features. Being transparent, we could see the positional relationship between the tubes, bronchi, and carina. A particular feature of our patient was the need to isolate and protect each ventilated lung from saline lavage. The model helped us to realize that a cuff inflated in the right main bronchus could easily obstruct the left main and right upper lobe bronchi, which made careful and accurate cuff positioning essential. We were also able to estimate the diameters and lengths of the correct tubes for placement and to design a number of approaches that may be successful. In addition, all members of the team were able to see the model and agree on a management plan before the procedure.

There were several limitations with the model. Its dimensions may not have been accurate enough because the child would have grown since the CT scan. A CT scan days before the lung lavage may have created a model more representative of the child, but a repeat CT scan was not justifiable on the grounds of airway imaging alone, given the radiation dose involved. We also recognize that there will be small variations in mucous membranes that may not be taken into account by a single CT image, although for the purposes of this study we felt that the lumen modelling was as accurate as possible.

Our model was rigid, unlike a real airway, which may have accepted larger tubes than those we tested. Printing using more compliant materials could make it more lifelike. Computed tomographic images during inspiration and expiration may help to illustrate the variation in dimensions, but our child’s respiratory function was not normal, and extra imaging may not have yielded useful extra data. The length of the model remains a problem. We were unable to model the entire airway structures from the lips to the vocal cords accurately because this information was not available (and is not typically acquired) from a thoracic CT data set. Airway length is likely at best to be approximated, because of variation with neck flexion.

Finally, accurate airway dimensions could lead to the creation of bespoke tracheal and bronchial single-lumen or double-lumen tubes. Bespoke tubes, made for individual patients, although potentially expensive, would offer an appealing solution to individualized patient care in the future.

In conclusion, we describe a novel application of 3D printing to create a model of a patient’s trachea and bronchi, which was valuable in planning complex airway management in a small child. The application of 3D modelling to airway management has the potential to improve intraoperative safety.

Authors’ contributions

Clinician testing 3D model and its application on the patient, writing up first draft of the paper, and revisions to the paper: C.A.W

Study design, acquisition of data to enable 3D model construction, and critical revision of paper for important intellectual content: O.J.A.

Clinician testing 3D model and its application on the patient, and final approval of the version to be published: A.E.B.

Lead for 3D model construction, revisions to the paper: S.S.
Assisted with later stage of 3D model construction, revisions to the paper: C.H.
Assisted with preliminary stage of 3D model construction and initial prototypes, revisions to the paper: S.vH.
Physician performing lung lavage, assisted with application of 3D model on the patient, critical revisions of paper for important intellectual content: C.W.
Substantial contribution to conception and study design, critical revisions of paper for important intellectual content: M.R.J.S.

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Declaration of interest
None declared.

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