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MODEL OF A TRACHEOBRONCHIAL TREE FOR THE TRAINING OF BRONCHOSCOPY EXAMINATIONS

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ABSTRACT

Simulation in medicine has been extensively used for the training of medical students, as well as for learning new procedures or studying complex situations, which need a deep understanding of the clinical case. Specifically, in anesthesia and intensive care, bronchoscopy is a procedure entailing some risks, such as perforation, bleeding or other emergency situations. Therefore, it is necessary to train residents with the use of alternative methods before practicing on patients.

In this context, we combined a physical model of the tracheobronchial tree with a virtual reality-based system to create a low-cost simulator for bronchoscopy training. Specifically, we designed and implemented a system combining a physical and a virtual model of the tracheobronchial tree of a specific patient, starting from his/hers CT image. This system represents an innovative simulator combining visual and haptic feedbacks. Indeed, our prototype is intended to enhance clinicians' skills in a riskless environment.

Keywords: medical simulation, bronchoscopy, 3D modeling, virtual-reality, 3D printing

1. INTRODUCTION

Breathing is one of the main vital functions allowing the human body to bring in oxygen and flush out carbon dioxide. The respiratory tract can be divided into upper and lower airways. The former includes nose, pharynx, and larynx; the latter comprises trachea, bronchi, and lungs. Trachea and bronchi form the tracheobronchial tree which is a tube running from the larynx to the lungs, and diverging in two bronchial tubes that branch off 15-20 times into smaller sections inside the lungs (Castano and Garberi 1983). When diagnostic imaging reveals pathological signs in the tracheobronchial tree, a bronchoscopy is required to navigate the tract. Bronchoscopy is an invasive procedure performed by pneumologists, thoracic surgeons or anesthesiologists (Geraci et al. 2007). Every year, around five hundred thousand of bronchoscopies are required in the United States (Colt, Crawford, and Galbraith III 2001). Nonetheless, such procedure has a mortality rate of 0.1% and can cause medical complications in nearly five out of one hundred procedures (Hehn et al. 2003). In this context, it is important to properly train students during their residency. However, the minimum number of bronchoscopies required to be proficient is not well defined. A study from 1980 indicated one hundred as minimum threshold to confidently perform a bronchoscopy (Faber 1978); nowadays the threshold raised up to five hundred (Ost et al. 2001; Konge et al. 2011). Due to the complexity of the procedure, the high risks involved, and the number of exams required to be proficient, medical simulation is a suitable tool for bronchoscopy training. Historically, bronchoscopy has been trained using animals (Raz et al. 2003; Al-Ramahi et al. 2016) , as well as videos of real exams and simulations (Kastelik et al. 2013; Davoudi and Colt 2009); later on, some mannequins have been developed, even though with big limitations. Specifically, they did not fully resemble a realistic tracheobronchial tree, and moreover, they were too rigid to be safely used with commercial bronchoscopes which are fragile and expensive (Colt, Crawford, and Galbraith III 2001). Currently, three groups of simulators are used: virtual, low-fidelity and computer-based high fidelity simulators (Colt 2013). Virtual simulators lack of the haptic feedback and users cannot practice but merely observe a procedure; low fidelity simulators include animal model navigated with real instruments; computer-based high fidelity are expensive simulators combining visual and haptic feedback for a complete simulation experience (Colt 2013).

2. OBJECTIVE

Our work focuses on the implementation of a tool for the training of pneumologists and anesthesiologists who need to perform bronchoscopy examinations using realistic tools. Specifically, we aimed at combining two technologies commonly used in medical simulation: physical mannequins and virtual reality (VR) environments, to create a realistic simulation experience, which can boost the learning process (Peyre et al. 2006).

Indeed, we realized a 3D model of a tracheobronchial tree, starting from a Computed Tomography (CT) image. Such model was 3D printed and imported into a graphic engine to create a virtual environment. The result is a combination of physical and virtual models communicating together in real time. In other words, information from an endoscopic camera navigating the upper airways model is sent to the VR so as movements of the real camera correspond to movement of the virtual one. The combination of virtual and real let residents learn about the anatomy of the tracheobronchial tree while practicing how to navigate the upper airways in both physiological and pathological conditions. The combined used of VR visualization allows the simulation of pathological conditions in order to improve the training outcome.

3. SYSTEM DEVELOPMENT

3.1. CT image segmentation

Starting from a CT image (DICOM; 0.625 mm/slide; Pitch factor 1.375), we segmented the data to isolate the bronchial tree, using the Hounsfield Unit scale and ITK-Snap software (Yushkevich et al. 2006). Hounsfield Unit is a grayscale proportional to the degree of x-ray attenuation (White and Pharoah 2018; Razi, Niknami, and Ghazani 2014) and it is particularly useful to isolate the upper airways since its lower limit corresponds to the air (Kalender 2011). Segmentation consists in partitioning an image into groups of pixels, in order to locate a specific object (Tan and Ding 2016). In other words, each pixel of an image is labelled according to specific features such as color, gray intensity etc. ITK-Snap is an open source software for the segmentation of medical images through manual and semi-automatic methods. In our study we choose a semi-automatic segmentation, which has reported to reduce user-dependent errors (Yushkevich et al. 2006). In detail, we defined a macro region of interest containing the bronchial tree; subsequently, we selected the Region Competition algorithm of active contour to create probability maps for the segmentation (Zhu and Yuille 1996). Then, we defined the position of the starting points, i.e. spherical seeds which will be merged together during the segmentation. Finally, we set the parameters for algorithm evolution and we started the procedure that was manually stopped once the result was satisfying (Fig. 1).

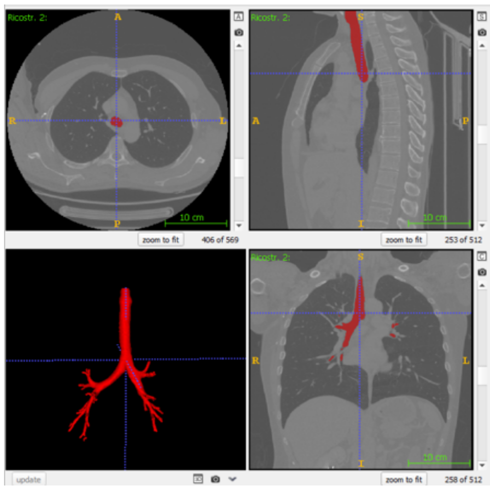

Figure 1. Digital model of the tracheobronchial tree obtained through the CT segmentation process.

3.2. Digital Model

At the end of the segmentation process, the tracheobronchial tree had 120 thousand vertices. Indeed, we reduced the number through a smoothing process, which makes the model both computationally lighter and geometrically more accurate. To do so, we imported the bronchial tree model into MeshLab, and we applied a three iteration Laplacian filter (Cignoni et al. 2008). After the smoothing, the model was imported into Rhinoceros 5© (https://www.rhino3d.com/, Robert McNeel & Associates, USA), a computer-aided design software (CAD) to be prepared for the 3D printing. Particularly, we added a 1-mm thickness and we divided the model into modules (Fig. 2), so that each module of the tracheobronchial tree had two opposite joints in the model reconstruction. This design choice was made for two reasons: firstly, the 3D printer we used had a build limit of 145x145x175ms; most importantly, such division of the model allows for modules substitution. In other words, it is possible to 3D print modules of different pathologies that can be added into the starting model, enhancing its usability. Briefly, each joint is oval-shaped and has either two holes or two nogs. In this way, the union of two intersections forms a linear joint connecting together different anatomical parts (Fig. 2).

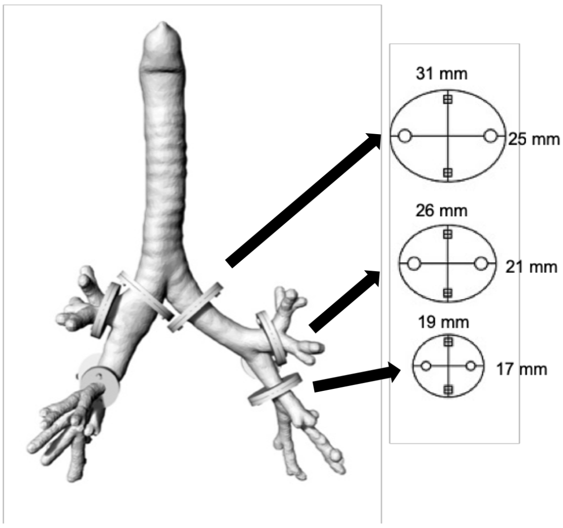

Figure 2. Left: digital model of the tracheobronchial tree divided into modules which are linked together with joints of different dimensions. Right: each circle represents a different measure of joint. Each module of the model has two opposite joints that can be linked to each other to create the tracheobronchial tree.

3.3. Physical Model

Once the model was ready, we printed it using the 3D printer Form 2 (FormLabs, USA), which is a stereolithographic 3D printer with a wide variety of resins. We selected a translucent resin that could be easily navigable by a bronchoscope (Fig. 3).

3.4. Virtual Reality

Afterwards, we imported the 3D model into Unity 3D (Unity Technologies, USA) to create the virtual reality environment for the bronchoscopy examination. Specifically, we inserted a Unity virtual camera to navigate the model, and we set the physical characteristics including:

- texture of the model;
- collisions between the model and the camera;

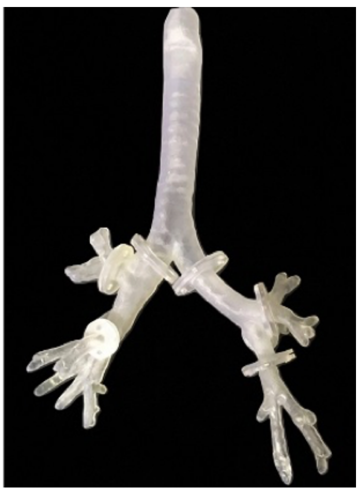

Figure 3. 3D printed model of the tracheobronchial tree

- view-blurring (redout) as a consequence of a collision;
- light settings to simulate the illumination effect of the broncoscope

The result is a realistic representation of the bronchial tree, as shown in Fig. 4.

3.5. Interaction between physical and virtual 3D model

Then, we connected the physical model with the virtual one through a client-server system, so as the virtual camera followed frame-by-frame the movements of the real endoscopic camera. In order to navigate the physical model and to replicate the movements in virtual reality, we solved the correspondence problem between real and virtual environments. In particular, we had to detect the exact position of the bronchoscope in the real model and to transfer this position to the virtual camera. To do so, we equipped the physical model with three Light Emitting Diodes (LEDs, Kingbright, USA; Fig. 5), each one with a different color (red λ=600 nm; orange λ=610 nm; yellow λ=588 nm). The three markers were positioned so as their location, from the point of view of the camera navigating the tree, corresponded to a triangle changing its dimension, according to the camera position. Moreover, the camera could capture different colors, depending on its rotation in the bronchial tree. Video frames from the endoscopic camera were analyzed in Matlab (Mathworks, USA). Specifically, each frame was decomposed into RGB (Red, Green, Blue) components, adding thresholds to separate the background from the light. The result was a binary image with light and background represented as 1 and 0, respectively. After an initial calibration phase, and assuming that the perimeter of the triangle composed of the three LEDs changes linearly with respect to the position of the camera, it was possible to reconstruct the camera location considering the lights position in the frame (Fig. 5).

4. CONCLUSIONS AND FUTURE DEVELOPMENT

This study aimed at the development of the first proof of concept of a bronchoscopy simulator. Starting from a CT image, we realized a low-cost and high-fidelity 3D model of the tracheobronchial tree. Additionally, we 3D printed it into modules which can

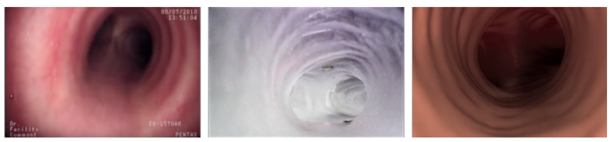

Figure 4. Left: image of a real bronchial tube, obtained with an endoscopic camera. Center: bronchoscope image of the physical model, realized through stereolithography. Right: frame from the virtual bronchoscopy examination.

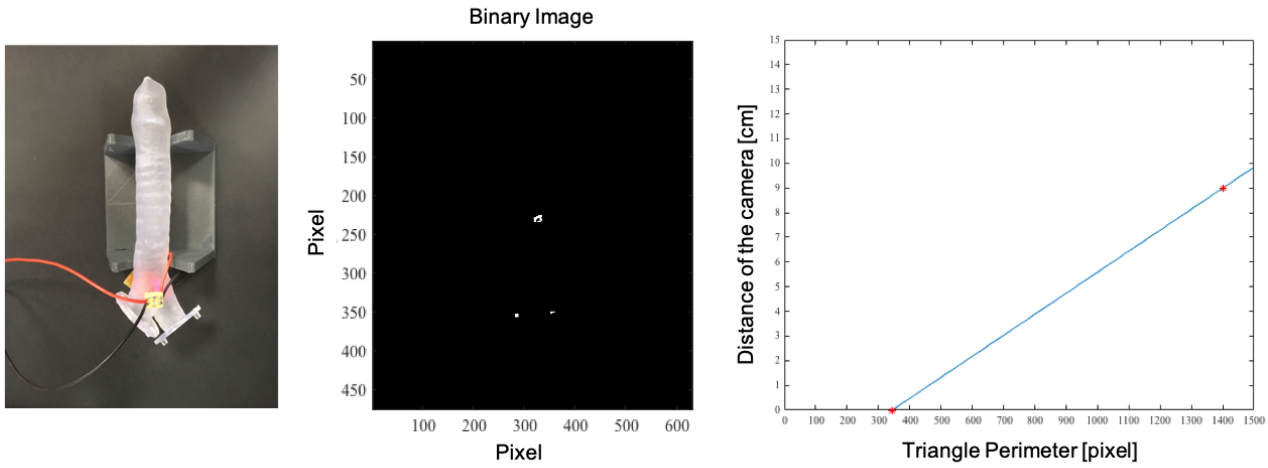

Figure 5: Left: physical Model equipped with LEDS to detect the position of the endoscopic camera. Center: Binary image used to determine the perimeter of the triangle formed by the LEDs, acquired by the camera in the physical model. Right: Relationship between LED-triangle perimeter and position of the endoscopic camera in the physical model.

be substituted to simulate different pathologies. This project may be used in different scenarios:

- to train residents who have to acquire basic skills;
- to simulate complex clinical cases before performing the bronchoscopy on the patient;
- to create a patient-specific tracheobronchial tree that guides the manufacturing of personalized stents.

Also, the way the simulator has been realized can be generalized to other medical procedures such as gastroscopy, colonoscopy, cystoscopy, etc.

The realization of the first prototype allowed us to define critical elements that need to be addressed to make the system more flexible. An important point is the development of new software for camera tracking, in lieu of physical sensors. Specifically, we equipped the physical model with LEDs, in order to solve the correspondence problem between real and virtual environments. Even though this is a robust solution, it has several practical issues such as the presence of hardware components (the LEDs) into the physical models which required calibration. Moreover, we assumed a linear relationship between the perimeters formed by the LEDs and the camera position in the physical model. This could not be valid in general. To overcome these issues, it would be possible to exploit computer vision techniques to extract visual features directly from the images captured by the bronchoscope. In detail, we will consider SURF (Speeded Up Robust Features) and SIFT (Scale Invariant Features Transform) approaches. Once detected the features on a sample of images captured in different physical positions, it is possible to apply a matching algorithm (e.g. the FLANN - Fast Approximate Nearest Neighbor) in order to detect the actual bronchoscope position. Such possibility would make the system completely plug-and-play. In other words, doctors can ask for a tracheobronchial tree, following the CT image, without any technical intervention other than the 3D printing. Also, our study should be replicated using CT images of different pathologies to evaluate the precision of the model in uncommon cases.

In conclusion, with our project we could evaluate the usability of patient-specific organs for endoscopy training. Results are promising and suggest that patient-based simulation should be pursued to make doctors more confident while performing clinical examinations. This would in turn reduce experience-dependent mistakes and error-related healthcare costs.

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