A method for quantitative measurement of gas volume changes in upper airway

TAO WANG AND ANUP BASU
DEPARTMENT OF COMPUTING SCIENCE, UNIVERSITY OF ALBERTA

Abstract

A method for quantitative measurement of gas volume changes in upper airway is presented in this paper. The aim of this study is to assess the feasibility of a novel Cone Beam Computerized Tomography (CBCT) technique for quantitative measurement of gas volume in upper airway. Our application is defining and tracking minute volume changes (a few milliliters) of airways caused by surgery, such as removal of tonsils in children, which increases volume. Doctors need to track the volume changes of airways for administering effective treatments. Traditionally, there are three ways to measure the gas volume in airway and lung. One is to use a spirometer. The second one is the plethysmographic method. The third one is the radiographic method. Spirometers are not able to measure minute volume changes of a few milliliters. The pleythysmographic method is not commonly used because it requires expensive additional equipment and is difficult for many patients to perform. Traditional radiographic method requires only a radiograph, but it is labor intensive and most studies were done in animals *in vitro*. The proposed process is a semi-automatic radiographic method. To the best of our knowledge, this is the most efficient radiographic method for quantitative measurement of gas volume changes in upper airway of human beings *in vivo*.

1. Introduction

Gas volume measurement in airway and lung is useful for the diagnosis and management of a variety of clinical conditions [1]. We consider the application of defining and tracking volume changes in airways caused by surgery such as the removal of tonsils in children. It is necessary for doctors to track such volume changes in order to administer effective treatments. In this case, the volume change of airways is only a few milliliters.

Three ways are traditionally used to measure the gas volume in airway and lung. The oldest way is to use a spirometer to measure the gas volume. It has been used for many decades. However, Spirometers are not able to measure minute volume changes of a few milliliters. Another problem [1] is that the exhaled or inhaled gas volumes and the volume actually measured by spirometers are not identical. The temperature of gas that occupies the airway and lungs is body temperature. As gas is exhaled, it cools to ambient temperature. According to Charles' law, as the temperature decreases the gas volume also decreases. Another way is the body plethysmography method. It is able to accurately measure [2] the intrathoracic gas volume. However, it is rarely used for some reasons [1, 3]. Firstly, the equipment is more expensive [1, 3] than spirometers. Secondly, it is difficult [3] for many patients to perform. The third way to measure gas volume in airway and lung is the radiographic method. It requires only a radiograph. Traditionally, intensive human-computer interactions [3] are required and most studies [4-5] were performed in animals *in vitro*.

The proposed process is a semi-automatic radiographic method performed in human beings *in vivo*. It requires much less user interactions. It is an efficient way to measure gas volume in airway and compare minute volume changes. It has three steps. Firstly, the Region of Interest (ROI) is located and cropped. Secondly, Confidence Connected Region Growing algorithm (CCRG) [6] is applied to segment the upper airway from the background. Thirdly, images are aligned (registered) by a coarse-to-fine matching method, and the gas volume is calculated and the volume changes are recorded. Most human-computer interactions occur in the first step. It is not a disadvantage because ROI is a subjective concept, which cannot be detected and cropped by computer automatically. The cropped ROI has reduced image dimensions, artificial region boundaries and simpler background. It enables the CCRG algorithm to do the segmentation reliably and quickly. The coarse-to-fine matching method creates a pyramid of images with different dimensions. At the beginning, it processes the images with smallest dimensions to get a coarse image alignment result. Then it processes the bigger images to find more precise alignment results, using the coarse result as guidance to narrow down the search ranges. In this way, image alignment is done efficiently. At last, the gas volume is calculated and the volume changes are recorded.

In the following sections, the methods and results will be described. In Section 2, we will briefly introduce the data collection, the tools and software we use, and how to locate and crop the ROI and segment the upper airway. Section 3 will discuss the coarse-to-fine matching method for image alignment and how to calculate the volume change. Results of experiments are presented in Section 4, before the work is concluded in Section 5.

2. Data collection and segmentation

A novel Cone Beam Computerized Tomography (CBCT) [7] technique is used to collect data from patients. Among all the advanced devices, we choose to use NewTom 3G because it has many superiorities [7] over its rivals and traditional CT devices. We use NewTom 3G to record two CBCT scans for a child patient. The first scan was taken before the surgery of removal of tonsil in May 2006. The second scan was taken in September 2006. The data is saved as DICOM [8] format. See Figure 1. It is very clear that the volume of upper airway increased after the surgery. We also asked some volunteers to two sets of CBCT scans for comparison. The first scan was taken in normal status. The second scan was taken when volunteer move mandible forward or horizontally. Figure 2 shows two volunteers, one move mandible forward while another one move mandible horizontally. We also attach some land markers on volunteer's face to facilitate segmentation.

The most difficult part of all radiographic methods is the data segmentation. We do not want to follow the traditional radiographic methods to manually do the segmentation. However, no general 3D airway automatic segmentation technique is available in such complicated background as shown in Figure 1. So we need to simplify the images to facilitate automatic segmentation approaches. In our case, we are only interested in the upper airway. Therefore, the ROI should be located and cropped to create smaller images with simpler background. The ROI can be easily located and cropped by comparing the positions of distinct bones and land markers in the images. Experts can locate and crop the ROI within a few seconds. In the cropped ROI, the upper airway is a connected region which is in the middle of the image with simpler background. CCRG algorithm works well to segment a connected region from a simple background in 3D space. A seed needs to be manually selected at the beginning. The CCRG algorithm then determines a data value range within a given standard deviation of the gray level of the seed. The seed grows in the ROI to include any voxel that falls within the above mentioned data value range. The grey level of the whole airway is almost the same value so that the CCRG can do the segmentation of airway well. One challenge for CCRG algorithm is that the background of the images is air, which has the same gray level with the airway. CCRG algorithm may expand to the background in some situations. Fortunately, the cropped ROI has some artificial region boundaries so that CCRG algorithm is restricted in the ROI. So it will not grow to the background. CCRG algorithm is implemented in some software packages, such as ScanIP/FE [9]. In our experiments, we use ScanIP/FE packages to do the segmentation. A segmented upper airway is displayed in Figure 3.

Figure 1. (Left) The yz plane of the CBCT scan taken in May 2006. (Right) The yz plane of the CBCT scan taken in September 2006

(a) (b) (c) (d)

Figure 2. (a) Volunteer 1, normal mandible (b) Volunteer 1, forward mandible (c) Volunteer 2, normal mandible (d) Volunteer 2, horizontally moved mandible

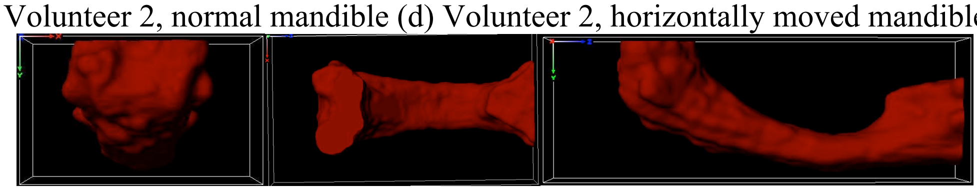

Figure 3. A segmented upper airway from 3 points of view

3. Volume change measurement and the coarse-to-fine matching method

The volume of airway can be calculated after segmentation is done. Figure 4 demonstrates the basic idea of volume change measurement. Suppose the small ellipse is the airway A1 before surgery and the big ellipse is the airway A2 after surgery. The volume of A1 is V1 + V0 and the volume of A2 is V2 + V0, where V0 is the volume of the intersection region of A1 and A2. There are two ways to calculate the volume change.

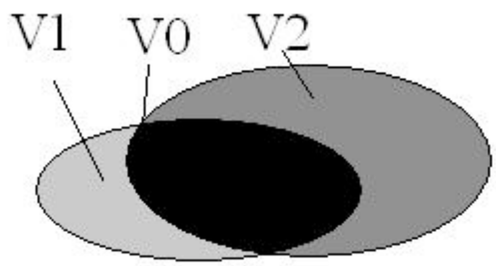

Figure 4. Volume change measurement

Since the volume of A1 is V1 + V0 and volume of A2 is V2 + V0, the most straightforward way is to take

$$(V2 + V0) – (V1 + V0) = V2 – V1 \qquad (1)$$

as the volume change.

Another way is to take

$$V2 \text{ (when V0 is maximized)} \qquad (2)$$

as the volume change. The airway is not rigid but flexible. The volume of airway changes all the time. The surgery of tonsil removal increases the volume of the upper airway. However, other factors, such as inhaling, exhaling or deformation, may increase or decrease the volume of the airway. Thus the volume of airway after surgery may be less than the volume of airway before surgery in some cases. If we take V2 – V1 as the volume change, it could be negative, which does not make sense. Since the volume of A1 is V1 + V0 and volume of A2 is V2 + V0, when V0 is maximized, V1 and V2 are minimized. Min(V1) represents the volume changed by other factors including inhaling, exhaling, deformation and etc. Min(V2) represents the volume changed by the surgery.

Minimizing V0 is a typical image alignment process. The goal of image alignment in the context of this paper is to

Find a 3D image transformation matrix M to minimize the volume of (A2 – A1 * M) (3)

A general 3D image transformation matrix has six degrees of freedom, rotations and translations in x, y and z axis. A complete search in the six dimensional space is extremely time-consuming and not feasible, especially for 3D medical images that have relatively big image dimensions. In our study, when people take CBCT with NewTom 3G, they are fixed in a surface so that the effect of rotations in x, y and z axis can be ignored. Some distinct bones and land markers are used to locate and crop the ROI. Images are aligned in the z axis during this process so that the translation in z axis can be ignored. Therefore we only need to align images considering translations in x and y axis.

To further speed up the image alignment process, we use a coarse-to-fine [10] matching method. It creates a pyramid of images with reduced dimensions in each layer. At the beginning, it processes the images with smallest dimensions to get a coarse image alignment result. Then it processes the bigger images to find more precise alignment results, using the coarse result as guidance to narrow down the search ranges. In this way, image alignment is done with high efficiency.

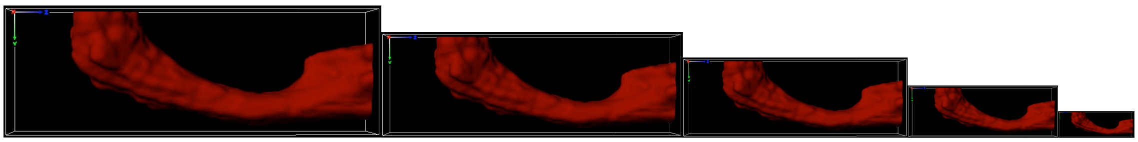

Figure 5. The image pyramid of the 3D airway

4. Experimental results

At this stage of our study, we have the CBCT images in DICOM format of a child patient and the images of two volunteers for the purpose of comparison. The experiment is done on an Intel Centrino Laptop with 512 MB memory. Table 1 shows the test data set. Table 2 shows results of image alignment and the time efficiency comparison for different methods when the search range is $x \in [-10mm, 10mm]$ and $y \in [-10mm, 10mm]$. It demonstrates that the coarse-to-fine matching method is more efficient than brute-force search. Table 3 compares the results of volume changes calculated by the two methods described in Section 3.

DICOM Models	**(x, y, z) resolution (mm)**	**number of image slices**	**total size on disk (MB)**
Patient, before surgery	0.250000, 0.250000, 0.500000	208	103
Patient, after surgery	0.250000, 0.250000, 0.511060	189	122
Volunteer 1, normal mandible	0.420000, 0.420000, 0.500002	391	195
Volunteer 1, forward mandible	0.419840, 0.420000, 0.498000	386	194
Volunteer 2, normal mandible	0.420000, 0.420000, 0.500000	395	197
Volunteer 1, horizontally moved mandible	0.420000, 0.420000, 0.500002	143	70.9

Table 1. The test data set.

3D Models	**(x, y) translations (mm)**	**Brute-force search time (s)**	**Coarse-to-fine search time (s)**
Patient	(-0.50, 1.50)	882	16.8
Volunteer 1	(-0.42, 0.00)	42.0	1.09
Volunteer 2	(-1.26,0.42)	38.0	3.54

Table 2. Image alignment results and time efficiency comparison for different methods.

3D Models	Min(V2) (ml)	V2 – V1 (ml)
Patient	4.2	2.6
Volunteer 1	3.8	2.7
Volunteer 2	1.7	1.0

Table 3. Comparison of volume changes calculated by the two methods.

5. Conclusions and future work

In this paper, we demonstrate how to quantitatively measure the volume changes for the upper airway. This initiative enables us to utilize a novel CBCT technique and test different methods in the area of 3D medical image segmentation and 3D image alignment. It requires much less user interactions than traditional radiographic methods and is time efficient. This method can be applied to many kinds of *in vitro* or *in vivo* gas volume measurement for both human beings and animals. The potential applications include the study of other airway problems such as obstructive sleep apnea, pulmonary gas volume measurement and clinical respiratory cares. There are a number of improvements that need to be made in the future. Firstly, we need to manually select a seed and specify a standard deviation to start the CCRG algorithm. This process can be performed automatically because the grey level of air is almost the same value in all the images and the standard deviation is small. We will apply some machine learning techniques to find out the mean grey level of air and a proper standard deviation in the near future. Thus, the whole process is fully automatic after the ROI is cropped, which must be done by human beings because ROI is a subjective concept. Secondly, because of constraints on time, our test data set has only patient and a few volunteers. Because the CBCT technique and the NewTom 3G is new to us, and some other unexpected reasons, only two volunteers' data is usable. Therefore, our test date set is very small. We will collect more data to test and validate our method in future work. Thirdly, we did not validate our results because we do not have body plethysmography devices and many other difficulties related to *in vivo* experiments for human beings. We need to cooperate with other research institutes to perform body plethysmography to validate our results and compare it with our methodology in the future.

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