The feasibility of three-dimensional displays of the thorax for preoperative planning in the surgical treatment of lung cancer

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Abstract

Objective: Three-dimensional (3D) displays of anatomic structures have become feasible for preoperative planning in some surgical procedures. There have been no reports, however, on the use of 3D displays for surgical treatment of lung cancer. We hypothesized that 3D displays of the thorax are useful for preoperative planning for lung cancer. Methods: Based on virtual reality technologies, we rendered 3D displays of the thorax from two-dimensional (2D) computed tomographic (CT) images of six anonymous patients, some of whom underwent surgical removal of lung cancer. For determining the resectability of lung cancer, we tested 17 participants with varying degrees of surgical skills to view 3D displays and read 2D CT images of these thoracic cavities in a randomized order. We measured their performance in terms of the accuracy of predicted resectability, the confidence of their prediction, planning time used, and workload experienced. Results: The results demonstrated that viewing 3D displays of thoracic cavities has significant advantages over reading 2D CT images in determining the resectability of lung cancer: increasing the accuracy of predicted resectability by about 20\%, enhancing the confidence of the prediction by about 20\%, decreasing planning time by about 30\%, and reducing workload by about 50\%. All participants preferred viewing 3D displays to reading 2D CT images for preoperative planning. Junior residents found 3D displays of thoraces more useful than senior residents. Conclusions: It is feasible to use 3D displays of the thorax for preoperative planning in treating lung cancer. Using 3D displays in surgical treatment of lung cancer has potential benefits, once the technique is perfected.

Keywords: Preoperative planning; 3D displays; Virtual reality; 2D CT; Lung surgery

1. Introduction

Cancer is the most serious health problem in North America and Europe. The latest figures produced by the American Cancer Society in the USA, the Ontario Cancer Registry in Canada, and the International Agency for Research on Cancer in Europe have predicted that about 3.5 million North Americans and Europeans will be diagnosed with cancer in 2005, and more than half of them will die from it\textsuperscript{1,2,3}. Among these reports, lung cancer ranks as the most prevalent form of cancer diagnosed, and the most common cause of cancer death. The treatment of choice for lung cancer is surgical resection. The primary challenge of this treatment method is to precisely determine the resectability of lung cancer, while preserving maximal lung function. Often without any input from a radiologist, a thoracic surgeon conventionally assesses this resectability by relying on his/her skills of reading two-dimensional (2D) computed tomographic (CT) images of the patient’s thorax using a standard 2D image reader. A resident needs to learn how to conduct this assessment during his/her training before he/she becomes a surgeon. In current clinical settings, such readers present 2D CT images in a single canonical viewpoint with monotonic shades of gray, as illustrated in Fig. 1. Reading 2D CT images is highly subjective, and demands strenuous mental computation to map anatomic structures from multiple 2D CT images onto actual thoracic cavities in three dimensions. The major disadvantage of this practice is low accuracy of predicted resectability, heavy workload, and long planning time.

Three-dimensional (3D) displays of anatomic structures are gaining an increasing popularity in surgical planning, as current advanced technologies of medical images and virtual reality (VR) continue to evolve. The advantages of 3D displays
over 2D images include: unlimited viewpoints; color illustration; stereoscopic view; and no need of mental reconstruction. Currently, the 3D displays of anatomic structures have become feasible for the determination of surgical methods and preoperative planning in brain, maxillofacial, liver, and gastric surgeries [1—4]. Many surgeons are enthusiastic about the progress in the research of 3D displays, and foresee the potential availability of 3D preoperative planning systems for training residents and practicing surgery [5—7]. They believe that the 3D displays will emerge as modern technologies for surgery, although the improvement of the current 3D displays requires significant further research and development.

Despite the enormous research efforts in the area of 3D displays for surgery, there has been little report on the use of 3D displays for the surgical treatment of lung cancer. Similarly, there is no evidence that supports the advantages of viewing 3D displays over reading 2D images in surgical planning for the treatment of lung cancer. Reading 2D CT images is the norm for surgical planning of treating lung cancer. The exception is the use of virtual bronchoscopy — 3D displays of the airway based on 2D CT images and VR technologies — as a diagnostic tool [8—10] and a training simulator [11—13]. Recently, Hemminger and colleagues [14] have reported a study on using 3D displays of a thorax for cardiothoracic surgery planning and diagnostic evaluation. Although it tested three surgeons and one radiologist, their study did not focus on preoperative planning of treating lung cancer because they analyzed mixed surgical cases (as opposed to lung cancer exclusively). Moreover, the results of the study suffered the drawback of subjectiveness, due to the use of invalidated questionnaires and the lack of objective and quantitative measurements, for example, measuring time used in surgical planning and diagnostic evaluation. Nevertheless, Hemminger’s study provided an initial step in using 3D displays of a thorax to communicate and plan surgery for some cardiothoracic cases.

Considering the use of virtual bronchoscopy and the initial step in using 3D displays of the thorax for some cardiothoracic surgery planning, it is necessary to have a study on how 3D display of the thorax improves the surgeon’s ability to assess resectability of lung cancer (i.e. whether lung cancer can be surgically removed) during the surgical planning. After all, it is a common practice for a surgeon to assess the resectability of lung cancer without input from a radiologist. Although a radiologist describes his/her findings from reading 2D CT images, a surgeon makes the ultimate decision regarding resectability. In addition, a resident needs to learn how to assess resectability during his/her training, although not making a decision about resectability alone in clinical settings. Therefore, we conducted a pilot study to prove the concept that 3D displays of the thorax are feasible in preoperative planning of treating lung cancer.

We hypothesized that preoperative planning using 3D displays of the thorax aids in determining the resectability of lung cancer, and focused on how 3D displays of the thorax affect assessing the resectability of lung cancer, when assessed by individuals possessing varying degrees of surgical skill.

2. Materials and methods

2.1. Thoracic cavities in 3D displays

With partial manual intervention, we processed stacks of 2D CT images to segment major anatomic structures of the thorax (such as lung lobes, the pulmonary vein and artery, the bony rib cage, and cancer lesions). We performed the segmentation by using the software amira 3.1 (Mercury Computer Systems Inc., France). With manual intervention, the average length of time for segmenting a stack of 2D CT images was about 2.0 h. On the basis of advanced VR technologies, a personal computer (PC) with high graphic quality (Dell Precision Mobil Workstation M60 plus a graphics card NVIDIA Quadro FX Go1000TM with 128MB Double Data Rate Video Memory) rendered these anatomic structures into 3D displays, as shown in Fig. 2. Each major anatomic structure has a unique color to distinguish it from the other anatomic structures. The spatial coordinates of all anatomic structures are the same as those in their corresponding 2D CT images. Thus, the 3D displays of thoracic cavities represent spatial information about the major anatomic structures, derived from and identical to those in the corresponding 2D CT images. Through a computer mouse, a user can manipulate the viewpoints and the size of these 3D displays. As well, the user can control viewing partial lung lobes in opacity or transparency for examining the spatial relationship of anatomic structures, which are normally inside of the lung lobes.

2.2. Study setup

Our approach was to compare 3D displays of thoracic cavities with 2D CT images in determining the resectability of lung cancer. On the same PC, the user can examine thoracic cavities by viewing their 3D displays and reading their corresponding 2D CT images. This study had ethics approval, following the Canadian Tri-council Guidelines of Research involving patients’ data and human participants.

In the study, original data sets were 2D CT images of thoracic cavities and pathological results. All data sets were from six anonymous patients who were referred from several different hospitals in Southern Ontario, and some of these
patients underwent surgical removal of lung cancer at the London Health Sciences Center (LHSC) in London, Ontario, Canada. The technical details of CT imaging, such as the manufacturer of CT scanners and the number of multiple slices, varied from patient to patient and were unknown to the surgeons at the LHSC. Some patients had resectable cancer lesions, and others had non-resectable cancer lesions. Since this study was an early work, for the simplicity of proving concept, these patients had no enlarged lymph nodes which indicate the severity of spreading cancer cells from the lungs into other parts of the body (nodal rendering have been planned in future projects). All data sets had the same image reader and the same procedure of pathological examination. From these stacks of 2D CT images, we derived their corresponding 3D displays by using the process described above.

This study involved human participants with varying degrees of surgical experience, from new residents to senior surgical residents who were in the last year of their residency. The number of thoracic surgeons available at the LHSC is too small to be included for statistical analysis. All 17 participants (10 junior residents in their post-graduate years 1–3, and 7 senior residents in their post-graduate years 4–7) had no physical impairment that would prevent them from writing and using a computer mouse. They had normal or corrected-to-normal vision, with a stereo-acuity of at least 40 in. arc as determined by the Randot Stereotest (Stereo Optical, Chicago, USA). They underwent an Ishihara color vision test (available at: http://www.richmondeye.com/colortest.htm) to ensure that they had no color blindness.

Each participant learned to use a 3D viewer for viewing 3D displays, and an image reader for reading 2D CT images of the thoraces. The participants examined six sets of 3D displays and six stacks of 2D CT images of the thoraces and were blinded to the actual outcomes (i.e. all participants were unaware of the actual resectability of each patient case in examination). Furthermore, the presenting order of these 3D displays and 2D CT images was randomized, to eliminate the awareness of the participants about the correspondence between a set of 3D displays and a certain stack of 2D CT images. By either viewing the 3D displays or reading the 2D CT images, the participants conducted a preoperative planning session to determine the resectability of the lung cancer. The length of a testing session is about 2 h for each participant.

The study utilized both quantitative and qualitative measures to evaluate the performance of each participant. The quantitative measures were in two folds: the time used in determining the resectability of lung cancer by viewing a set of 3D displays (or by reading a stack of 2D CT images) and the error rate of the predicted resectability by answering an empirical questionnaire. We compared the pathological data of the patients with the responses to determine the accuracy (error rate) in the predicted resectability of lung cancer.

The qualitative measures were used to assess the confidence on the accuracy of predicted resectability, and the workload that each participant experienced during
viewing a 3D display or reading a stack of 2D CT images. The qualitative measures of workload were based on the validated NASA Task Load Index [15]. Each participant filled in a workload table after viewing a 3D display (or reading a stack of 2D CT images) of a thorax, by indicating a scale from 0 to 100 (at an interval of 5) for each qualitative measure and ranking all measures in terms of their contribution to his/her experienced confidence and workload.

For the same patient, we compared the quantitative and qualitative measures between viewing a 3D display and reading a stack of 2D CT images. We used the statistical method of ANOVA (analysis of variance) to analyze these measures. Statistical significance was at 5%.

3. Results

For all 17 participants, the ANOVA analysis of the quantitative and qualitative measures indicated significant differences between viewing 3D displays and reading 2D CT images of the thorax in determining the resectability of lung cancer [the accuracy of predicted resectability: $F(1, 16) = 8.577, p < 0.05$; the confidence of the prediction: $F(1, 16) = 30.737, p < 0.001$; planning time used: $F(1, 16) = 15.770, p < 0.01$; workload experienced: $F(1, 16) = 42.342, p < 0.001$]. As shown in Fig. 3, viewing 3D displays of the thorax has advantages over reading 2D CT images in increasing the accuracy of predicted resectability by about 20% (mean accuracy for viewing 3D displays: 28.82% vs reading 2D CT images: 5.49%); enhancing the confidence of the prediction by about 20% (mean confidence index for viewing 3D displays: 4.08 vs reading 2D CT images: 3.23); decreasing planning time by about 30% (mean time length for viewing 3D displays: 2:50 min:s vs reading 2D CT images: 3:45 min:s); and reducing workload by about 50% (mean workload index for viewing 3D displays: 414 vs reading 2D CT images: 767). These results would be significant in a typical clinical day for saving about 30.0 min to 1.0 h of planning time with increased accuracy and confidence of predicting resectability, and decreased experienced workload. All participants expressed their preference of viewing 3D displays to reading 2D CT images of thoracic cavities.

In general, the level of mastering the skill of reading 2D CT images is directly proportional to the number of years in residency training. It would therefore be interesting to know whether viewing 3D displays of thoracic cavities for determining resectability of lung cancer has different effects for junior and senior residents in the study. We analyzed the difference between reading 2D CT images and viewing 3D displays of thoracic cavities for 10 junior residents and 7 senior residents, respectively. The ANOVA analysis of the quantitative and qualitative measures demonstrated that junior residents benefit significantly more from viewing 3D displays of thoracic cavities in determining the resectability of lung cancer than senior residents. [The accuracy of predicted resectability: junior residents, 3D vs 2D, 25.67% vs 1.33%, $F(1, 9) = 7.244, p < 0.05$; senior residents, 3D vs 2D, 33.33% vs 11.43%, $F(1, 6) = 2.039, p < 0.05$. The confidence of the prediction: junior residents, 3D vs 2D, 0.47 vs 3.05, $F(1, 9) = 27.249, p < 0.01$; senior residents, 3D vs 2D, 4.10 vs 3.48, $F(1, 6) = 6.783, p < 0.05$. Planning time used: junior residents, 3D vs 2D, 2:46 min:s vs 3:49 min:s, $F(1, 9) = 10.290, p < 0.01$; senior residents, 3D vs 2D, 2.56 min vs 3.40 min, $F(1, 6) = 5.085, p = 0.065 > 0.05$. Workload experienced: junior residents, 3D vs 2D, 376 vs 793, $F(1, 9) = 54.690, p < 0.001$; senior residents, 3D vs 2D, 469 vs 745, $F(1, 6) = 6.996, p < 0.05$]. As shown in Fig. 4, junior residents found 3D displays of thoracic cavities more useful than senior residents in determining resectability of lung cancer, because the junior residents improved more in the accuracy and confidence of predicted resectability from viewing 3D displays versus reading 2D CT images of thoracic cavities than their senior counterparts. An explanation of this observation might be that the junior residents have fewer exposures to reading and interpreting 2D CT images than their senior counterparts, even though both groups of residents have similar training in the 3D anatomic structures of the thorax. As a result, the junior residents discover that the 3D displays of thoracic cavities are more intuitively in agreement with the 3D anatomic structures of the thorax. Nevertheless, both groups of junior and senior residents demonstrated the same trend of benefits from using 3D displays of thoracic cavities for their surgical planning. This observation implies the potential benefit of using 3D displays of thoracic cavities to train surgical residents.
4. Discussion

Surprisingly, the advantages of viewing 3D displays in surgical planning of treating lung cancer seem to contradict the minor advantage of viewing 3D displays in learning anatomy from computers. Recently, Garg and colleagues [16–18] have conducted a series of studies to examine the role of viewing 3D displays of anatomic structures in learning anatomy compared with reading 2D canonical presentations of the same structures. In learning anatomy from computers, they have observed that viewing 3D displays provides minimal advantages over reading 2D presentations with canonical viewpoints to some learners, and may disadvantage learners with poor spatial ability. Learners have accumulated most spatial information about anatomic structures from canonical viewpoints, although they could manipulate multiple viewpoints in viewing 3D displays.

This discrepancy might arise from the different use of the spatial information about anatomic structures in surgical planning and learning anatomy, respectively. Surgical planning not only requires the generalized spatial information about anatomic structures that are similar for the majority of the human population, but also the detailed differentiation that each individual patient might have. Most differentiation, unfortunately, could be visible only from certain non-canonical viewpoints (or unfamiliar orientations). The features of unlimited viewpoints and easy manipulation that 3D displays of anatomic structures offer would, no doubt, facilitate the acquisition of this differentiation along with its other characteristics of transparency and removing partial structures.

In contrast, learning anatomy is to generalize spatial information about anatomic structures into a mental representation, which describes their principle characteristics for the majority of the human population. As Garg and colleagues have found, certain canonical viewpoints (or familiar orientations) of anatomic structures play important roles in learning anatomy [16–18]. Their findings are in agreement with theories for the mental representation of spatial objects, which claim that humans remember spatial relationships of objects in canonical viewpoints and recognize non-canonical viewpoints by mentally rotating from these canonical viewpoints [19].

For this study, we derived 3D displays of thoracic cavities from stacks of 2D CT images. In other words, stacks of 2D CT images of thoracic cavities are raw data for constructing corresponding 3D displays on advanced computers. The advantages of the 3D display are that it enhances the accuracy and confidence of predicted resectability and relieves the user from the mental computation involved in mapping the 2D CT images into actual 3D thoracic cavities. These advantages, combined with the superior viewing characteristics of 3D displays (such as unlimited viewpoints, easy manipulation, transparency, and removing partial structures), readily explain why all participants of the current study generally prefer viewing 3D displays to reading 2D CT images for their surgical planning of treating lung cancer. Further, it explains why junior residents benefit more than senior residents from viewing 3D displays. Nevertheless, this representation is selective to represent major anatomic structures of the thorax (such as lung lobes, the pulmonary vein and artery, the bony rib cage, and cancer lesions). In the current study, the information about other anatomic structures of thoracic cavities (such as lymph nodes) was not considered in restructuring 3D displays from corresponding 2D CT images. Consequently, these 3D displays contain subsets of information, which are available in corresponding 2D CT images. These subsets of information might reveal how senior residents use 3D displays of thoracic cavities for their surgical planning, because they were looking for information (such as lymph nodes) which was not available for them in 3D displays, and was not verbally instructed to them before the study either. This observation points to the usefulness of 3D displays in training surgical residents, by selectively presenting anatomic structures and diseased tissues.

These subsets of information about the thorax in 3D displays would not impact the importance of the findings in the current study, nor would the small number of data sets and participants involved in this study. As described earlier, the objective of this study is to prove the concept of feasibility in using 3D displays of thoracic cavities for preoperative planning of treating lung cancer, rather than to investigate the suitability of the 3D displays for surgical planning in clinical practice (for a detailed study on this

![Fig. 4. Comparison between junior and senior residents in determining the resectability of lung cancer. (a) Planning time. (b) Workload. (c) Accuracy of predicted resectability. (d) Confidence of the prediction. (Error bars represent the standard error of the mean difference.)](https://academic.oup.com/ejcts/article-abstract/31/3/506/511786)
issue, please refer to [14]). Indeed, the results of this study have achieved this objective in a relatively inexpensive fashion. We recognize that, from now on, there will be a long journey of putting research efforts into improving many technical issues and to undertake exhaustive evaluation, before 3D displays of thoracic cavities are suitable for surgical planning in clinical practice. Currently, some technical issues for improvement are as follows: (1) decreasing manual intervention in segmenting anatomic structures of thoracic cavities to shorten segmenting time and to increase segmenting objectiveness; (2) including the information of lymph nodes in thoracic cavities from 2D CT images and positron emission tomographic images; (3) developing intuitive human-computer interface to facilitate the viewing manipulation of 3D displays for the user. All of these improvements are achievable, given current research progress in the other fields related to develop 3D displays of anatomic structures.

In contrast to the study of Hemminger and colleagues [14], we focused on how the 3D displays of the thorax affect assessing the resectability of lung cancer with different degrees of surgical skills by blinding the actual outcomes to all participants. We found that, with all degrees of surgical skills, 3D displays of the thorax have advantages over 2D CT images in increasing the accuracy of predicted resectability, enhancing the confidence of the prediction, reducing workload, and decreasing planning time.

In conclusion, we proved the concept that it is feasible to develop 3D displays of the thorax from 2D CT images for preoperative planning of treating lung cancer. This forecasts benefits for using 3D displays of the thorax in such surgical planning, once the technique is perfected.

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References


