

Assessment of Real-Time 3D Visualization for Cardiothoracic Diagnostic Evaluation and Surgery Planning

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Rationale and Objectives: Three-dimensional (3D) real-time volume rendering has demonstrated improvements in clinical care for several areas of radiological imaging. We test whether advanced real-time rendering techniques combined with an effective user interface will allow radiologists and surgeons to improve their performance for cardiothoracic surgery planning and diagnostic evaluation. **Materials and Methods:** An interactive combination 3D and 2D visualization system developed at the University of North Carolina at Chapel Hill was compared against standard tiled 2D slice presentation on a viewbox. The system was evaluated for 23 complex cardiothoracic computed tomographic (CT) cases including heart-lung and lung transplantation, tumor resection, airway stent placement, repair of congenital heart defects, aortic aneurysm repair, and resection of pulmonary arteriovenous malformation. Radiologists and surgeons recorded their impressions with and without the use of the interactive visualization system. **Results:** The cardiothoracic surgeons reported positive benefits to using the 3D visualizations. The addition of the 3D visualization changed the surgical plan (65% of cases), increased the surgeon's confidence (on average 40% per case), and correlated well with the anatomy found at surgery (95% of cases). The radiologists reported fewer and less major changes than the surgeons in their understanding of the case due to the 3D visualization. They found new findings or additional information about existing findings in 66% of the cases; however, they changed their radiology report in only 14% of the cases. **Conclusion:** With the appropriate choice of 3D real-time volume rendering and a well-designed user interface, both surgeons and radiologists benefit from viewing an interactive 3D visualization in addition to 2D images for surgery planning and diagnostic evaluation of complex cardiothoracic cases. This study finds that 3D visualization is especially helpful to the surgeon in understanding the case, and in communicating and planning the surgery. These results suggest that including real-time

3D visualization would be of clinical benefit for complex cardiothoracic CT cases.

KEY WORDS: 3D, volume visualization, surgery planning, diagnostic evaluation, cardiothoracic, computed tomography, radiology workstation

IMAGE DISPLAY AND ANALYSIS

The display of "volume" datasets acquired in computed tomography (CT), magnetic resonance imaging (MRI), and other radiology mo-

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dalities has traditionally been done by presenting sets of image "slices" through the volume to the radiologist, usually in a tiled format. With the advent of faster computers, and advanced computer graphics algorithms, the possibility of rendering the volume directly as a three dimensional (3D) view of the body became possible. Three-dimensional visualization has already demonstrated benefits in conjunction with CT including angiography, cerebral aneurysms, dental implants, liver transplants, cranio-facial surgery, renal anatomy, radiation treatment planning, temporal bone surgery, virtual cystoscopy, virtual endoscopy, virtual colonography, virtual bronchoscopy.¹⁻²¹ However, there has been limited work applying real-time 3D volume visualization to CT cardiothoracic surgery planning and diagnostic evaluation.

A combination of factors has made possible the CT acquisition of high-quality volume datasets, which facilitate 3D volume rendering. The most important change has been the advent of spiral CT which allows a single scan to quickly cover a sizable 3D volume. Additionally, when combined with breath-holding by the patient, the 3D stack of slices or volume is well registered and suitable for high-quality 3D visualization techniques.²²⁻²⁴ Further improvements have come with multislice detectors which support faster scan rates allowing shorter breath holds to cover more anatomy. Finally, administration of intravenous (IV) contrast material enhances the contrast difference between vessels of interest and surrounding tissues. Spiral CT studies with contrast material are standard practice in most departments.

The real-time 3D visualizations evaluated in this study were done using the SeeThru real-time 3D display application, which was developed in the radiology department at the University of North Carolina at Chapel Hill (UNC).²⁵⁻²⁷ SeeThru runs on an SGI Reality Engine computer graphics workstation (Silicon Graphics Inc., Mountain View, CA). It was developed to take advantage of developments in computer graphics hardware architectures and software algorithms to depict 3D volumes on 2D video monitors at interactive update rates so that the human observer will have a sense of the 3D scene. The appearance of a 3D scene from a static 2D image can be accomplished using visual cues such as occlusion, perspective, shading, and stereo (when using stereo display and glasses).

Further, if the observer can manipulate the image on the screen, additional rotational cues are added, as well as strengthening the previous cues.²⁸ SeeThru was developed at UNC specifically for radiology and surgery applications.^{26,27,29} It supports the real-time (faster than 20 frames/s) modification of all viewing parameters (rotation, zooming, etc.), clipping cutplanes, and classification (ability to select specific tissues types, or portions of volume). In pilot work leading up to this and other studies,^{29,30} we found opacity and gradient-based 3D rendering methods to be more effective than previously used visualization techniques. Surface-based renderings³¹ have difficulties accurately depicting soft tissue to soft tissue interfaces common in cardiothoracic cases.²⁷ Simpler, less visually realistic real-time direct volume rendering techniques such as MIP^{32,33} can only depict the brightest contrast location in projections of the volume, limiting their effectiveness to primarily vascular depictions. Finally, cine loop or still frames of similar high-quality direct volume rendered images are not as effective because they do not provide the crucial kinetic depth effect cues.^{25,34} Further, they do not let the user explore the volume. These tradeoffs were studied by Ware and Franck,³⁵ who compared the relative merits of many of the 2D and 3D cues available when displaying a 3D volume on a computer screen and found that real-time 3D viewing, combined with hand control for rotation of the object, was the most accurate, as well as one of the fastest interactions. Additionally, they found cine rotations were slightly worse than user controlled 3D, whereas a simple 2D still picture provided the least comprehensible visualization.

MATERIAL AND METHODS

Patients

In our preliminary work, we found the 3D visualizations more helpful for complex cardiothoracic cases. We believe this is due, at least in part, to radiologists' extensive training which enables them to recognize and effectively comprehend normal or common anatomy using 2D visualizations. As a result, we chose to evaluate the 3D visualization only on complex cardiothoracic cases where we believed it would be most useful clinically. We asked our cardiothoracic surgeons (THE and FCB) to select cases from the UNC cardiothoracic clinic that they considered complex. All training and study cases were from these selected complex cardiothoracic cases. Prior to the study, we retrospectively piloted

the same acquisition and visualization methods on 10 patient cases from the cardiothoracic clinic. After finalizing both scanning and visualization protocols for each of the six case types, we prospectively acquired 23 consecutive adult cases from the cardiothoracic clinic for the study. The cases included six types of cardiothoracic surgical procedures including heart–lung and lung transplantation ($n = 8$), tumor removal ($n = 6$), airway stent placement ($n = 6$), repair of congenital heart defects ($n = 2$), aortic aneurysm repair ($n = 1$), and resection of pulmonary arteriovenous malformation ($n = 1$). Images were acquired on a Siemens Somatom Plus spiral CT scanner (Siemens Medical Systems, Iselin, NJ), using single breath-hold spiral acquisitions.

All studies were reviewed and included in the analysis except for those not reviewed by the surgeons because the transplant recipient died prior to the donors being evaluated. Three cases had partial data because the transplant recipient patient improved prior to surgery ($n = 2$), or the planned surgery was ruled out after the review with the 3D visualization ($n = 1$).

CT Scanning and Reconstruction

The protocol for the cardiothoracic cases was 90 to 120 ml Omnipaque 300 administered via power injector through the antecubital vein at 2 to 3 ml/s. Scanning was begun approximately 20 s after initiation of contrast administration. All studies are 512×512 pixels in each individual slice. Zoom factor was set to include the entire chest area, while attempting to minimize the dead space surrounding the patient imaged. The slice thickness acquisition was one of 8/8/4, 5/5/3, 3/3/2, where the first number is the rate of CT table feed in

millimeters per second; the second number is the acquisition slice thickness in millimeters; and the third number is the reconstructed thickness in millimeters. Scans were generally acquired at the thinnest slice thickness possible that covered the desired anatomy in a single breath-hold of the patient, while not subjecting the patient to more than the normal radiation dosage. Based on our prior experience and other's work,²³ we chose to reconstruct spiral datasets in slices spaced approximately half of the acquisition thickness. The standard Siemens reconstruction algorithms were used to reconstruct the datasets. For these soft tissue studies the Siemens scanner was set to use the "slim" reconstruction interval with the "standard" filter.

Visualization Technique

Once the study was acquired on the scanner, it was transmitted electronically over a network connection to the 3D workstation in 1 to 2 min. Unlike other methods that require preprocessing of the data, the SeeThru visualization is available upon receipt of the study by the 3D workstation. This enables the study to be reviewed immediately after the scan is completed, as well as making possible remote consultation at any computer in the hospital or on the Internet. Patient studies were acquired in 512×512 pixels, of up to 64 slices, creating a $512 \times 512 \times 64$ volume. These volumes were rendered under the interactive control of the physician on the SGI workstation. An opacity-based direct volume rendering algorithm was used which did not incorporate gradient information and had a fixed light source. All aspects of the visualization including rotation, zoom, transparency, and

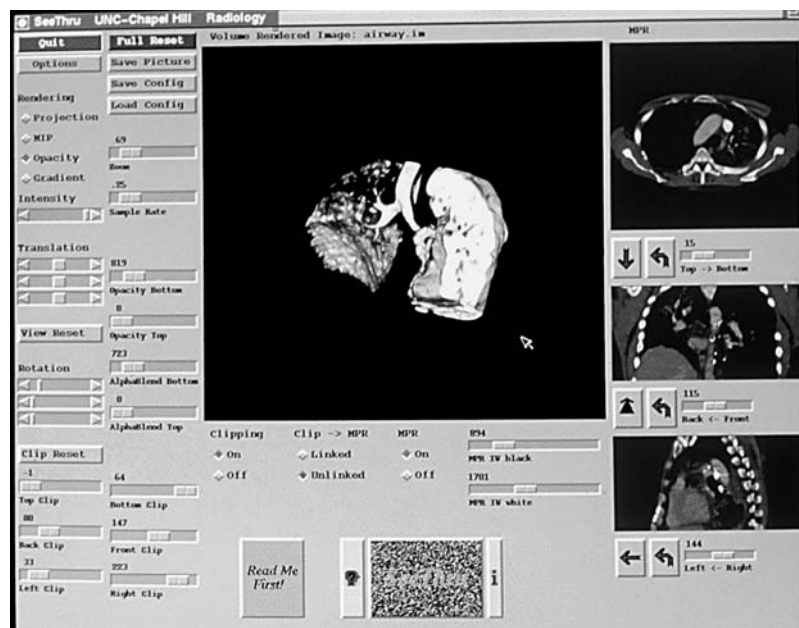


Fig 1. Standard layout of a SeeThru presentation. At the center top is the 3D visualization that is under real-time control by the user. Changes to parameters of the model, the visualization, clipping, etc., via the interaction controls on the left side change the 2D and 3D visualizations in real-time. The user can also use the mouse to rotate the 3D object or scroll through the 2D slices for a more natural interface. On the right side of the screen are the three MPR views.

classification were under interactive control via the mouse and user interface, with the screen updated at approximately 10 frames/s. A complete description of our hardware and software methods is described in Hemminger.²⁷ Figure 1 shows the SeeThru interface with a living lung donor case with the airways classification preset setting. Note that SeeThru shows both 3D and 2D presentations, with the 2D slices presented via three multiplanar reformatted windows, which can scroll through the study from three orthogonal axes. In this paper, we will refer to the SeeThru visualization as the 3D visualization because the primary usage of SeeThru in the study by the surgeons and radiologists was of the 3D volume rendered window. Protocols were developed for each type of study for which 3D visualizations were utilized. This enabled each study to automatically come up with preset visualization settings appropriate for the individual case type. The clinician would then adjust the viewing parameters to optimize the visualization for the anatomy of the specific case. This usually took 10–20 s. Then the clinician would spend time rotating, zooming, and cutting away the anatomy, as well as utilizing different classifications (for instance, airway and vascular classifications on living lung donor transplant cases) as part of the treatment planning.

The real-time 3D visualizations and interactive 2D multiplanar reformat (MPR) views that were utilized by SeeThru in this study are now available on most major commercial systems supporting opacity-based 3D real-time or near real-time volume rendering, including such products as GE Advantage Windows, Siemens Virtuosio, Vital Images Vitrea, and Voxar PlugNView 3D.

Study Design

Because of patient care considerations, the study design was for the computer-based 3D volume rendered plus 2D stack visualization (SeeThru), to be evaluated as an adjunct to the existing standard of care, the tiled 2D film presentation. Thus, both the radiologist and the surgeon would see cases as they normally would, and then, in addition, they would review the case with the SeeThru visualization tool available. The overall hypothesis was that the addition of the 3D visualization would change (improve) clinical care. Separate questionnaires were designed for the radiologist and surgeon to elucidate how the addition of the 3D visualization caused quantitative changes (changes to the surgery plan, changes to the radiologist report, changes in radiologist reported findings) as well as qualitative changes (radiologist's understanding of the case, radiologist communication of the case to the surgeon, correlation of anatomy seen in 3D with patient at surgery, surgeon's understanding of the case, surgeon's confidence in their surgical plan before and after using the 3D). The complete questionnaires are available on the web.^{36,37} We chose not to try to analyze the length of viewing times because they are highly variable due to the consultation type setting, the surgeon's use of the 3D visualization for treatment planning while viewing the study, interruptions, etc.

Protocol

First, the radiologists would review the films on the body CT alternator viewbox as part of their standard clinical routine.

When the surgeon was available, he would contact the radiologist and they would review the films on a viewbox in their standard manner. This was the standard clinical procedure. Then, after they had decided their initial opinions of the case, they would both review the 3D visualization of the case together on the workstation. The films remained available on an adjacent viewbox for comparison. After this review the radiologist and surgeon filled out their questionnaires. Lastly, after the surgery was performed, the surgeon completed the remaining questions on the surgery form that correlated surgical findings with what they saw earlier on the 3D visualization. No time limits were placed on any of the viewings or analyses. Responses from the forms were coded by the experimenters into computer data files, which were then analyzed using SAS (SAS Institute, Cary NC).

Observers

There were three surgeons who participated in the study. One surgeon participated in only one case, with the rest divided fairly evenly between the other two surgeons. All three surgeons were senior faculty, with extensive experience. There was a single radiologist participant, who was the senior thoracic radiologist and the primary reader for cardiothoracic cases in the department.

RESULTS

The results from the radiologist's and surgeon's study questionnaires are presented first in tabular form (Tables 1–7). Additionally, an analysis was performed to attempt to put a greater statistical level of significance on these results. For the dichotomous variables (change of radiologist report, change of surgical plan), 95% confidence limits were placed on the proportion of positive responses following the method described in Johnson et al.³⁸ (Tables 1 and 2). Table 3 summarizes across all 23 cases the changes in radiologist's individual findings, grouped by significance of finding. The remaining categorical variables are displayed as histogram tables counted across the 23 cases in the study. The 95% confidence intervals about the median are given as well. Because the data for these variables are discrete and the sample size for this study is small, the median is the best measure of central tendency. The confidence intervals were derived using a method based on randomization.³⁹ These results for the categorical variables are shown in Tables 4–7.

Dichotomous Variables

The results reveal that 13.0% of the radiologists' reports were changed due to the 3D

Table 1. Number of cases (3/23) in which the radiologists changed their report as a result of additionally viewing the 3d visualization

3D Visualization...	Number of cases	Percentage of cases (%)
Changed radiology report	3	13
Did not change radiology report	20	87

visualization [the 95% confidence interval is (2.8,28.0)]. These results are shown in Table 1. An example of a changed radiologist report was a case where the 3D visualization demonstrated “narrowing of the origin of the left carotid artery (which was) not appreciated on 2D images.”

In comparison, surgeons changed their surgical plan in 65.2% of the cases as a result of the 3D visualization [the 95% confidence interval is (42.7,80.3)]. These results are shown in Table 2. If the surgery plan was changed, the surgeons were required to list the changes to their surgical plan. For example, for a severe bronchial stenosis case the surgeon indicated four changes occurred because of seeing the 3D visualization: “1) was more confident the patient would survive operative intervention; 2) made an approach to the right bronchus seem feasible; 3) planned to use the silastic rather than wire stent; 4) realized distal airways were patent.”

The radiologists were asked to list the individual findings in each case and rate how well they were seen with the 3D visualization compared to without the 3D visualization. Their ratings for all the findings are summarized across the cases and shown in Table 3. In a heart–lung transplant for a congenital heart defect case, the radiologist listed two findings: the “complex cardiovascular anatomy relationship” was seen better on 3D, and the “narrowed origin of a great vessel off the interrupted aortic arch” was seen exclusively on the 3D visualization. In a living lung donor case, the radiologist reported that the “precise identification

Table 2. Number of cases (8/23) in which the surgeons changed their surgery plan because of seeing the 3d visualization

3D Visualization...	Number of cases	Percentage of cases (%)
Changed Surgery Plan	15	65
Did not change surgery plan	8	35

Table 3. Groupings of findings, across all 23 cases, based on whether the finding appeared to the radiologists the same as on film (no difference, 9/27), or visualization of the finding was improved: better on 3d (15/27) or exclusively seen only on the 3d (3/27)

Findings found by the radiologists were...	Number of findings	Percentage of findings (%)
Worse on 3D	0	0
No different	9	33
Better on 3D	15	56
Exclusively on 3D	3	11

and delineation of bilateral middle and lower lobe pulmonary vasculature and its relationship to corresponding airway anatomy” were seen exclusively on the 3D visualization, and that “small pulmonary vessels” were seen better in the 3D visualization.

Categorical Variables

The 95% confidence interval for the radiologist’s question “Was 3D visualization helpful in *your* understanding the case?” was (‘no difference’, ‘slightly better’), with the results shown in Table 4.

For the radiologist’s question of “Was the 3D visualization clinically helpful to the radiologist when *conveying* your understanding of a case to the surgeon?” the 95% CI was (‘slightly better’, ‘moderately better’). These results are seen in Table 5.

For the surgeon, the 95% CI for how well the 3D visualization corresponded with what the surgeon saw at surgery was (‘moderately good match’, ‘very good match’). These results are tabulated in Table 6. There was only one case in which a good match was not reported between the 3D visualization and what was seen at surgery. In that case, the surgeon reported “we missed a large

Table 4. List of the number of cases based on the 3d visualization’s effect on radiologist’s understanding of the case

3D Helped radiologist understanding of the case; made...	Number of cases	Percentage of cases (%)
Worse	0	0
No difference	9	40
Slightly better	10	43
Moderately better	4	17
Significantly better	0	0

Table 5. Summary of the numbers of cases where the radiologists believe the 3d visualization helps them communicate information about the case to the participating surgeon

3D Helped radiologist convey information to surgeon; made...	Number of cases	Percentage of cases (%)
No difference	4	17
Slightly better	7	31
Moderately better	8	35
Significantly better	4	17

posterior ascending branch [connecting] the right upper lobe coming off the superior segment artery to the lower lobe.” This is a drawback of the 2D display. Although allowing the observer to rotate the anatomy on the 2D display screen gives a good sense of the 3D anatomy, it is not as conveniently appreciated as on a true 3D display. In the future, a true 3D visualization display technology might help reduce this type of error.

For the surgeon’s question “Was the 3D visualization clinically helpful based on what was seen at surgery?” the 95% CI is (‘slightly better’, ‘significantly better’) and summarized in Table 7. In every case the surgeons indicated the 3D visualization helped clinically. An example of this from comments written on the form by the surgeon in a heart-lung transplant case: “It [the 3D visualization] was essential. I doubt we would have been able to perform the procedure successfully without it—and this information could not be gotten from the 2D CT. An angiogram might have provided some of the information.”

The last question analyzed on the surgical report asked what the surgeon’s confidence in their surgical plan was before and after using the 3D visualization. The addition of the 3D visualization always resulted in increased confidence in the surgical plan. The mean confidence prior to the addition of the 3D visualization was 45% (out of

Table 7. The surgeons’ judgment on how helpful the 3d visualization was to them in performing the surgery

3D Visualization made the surgery plan...	Number of cases	Percentage of cases (%)
Significantly worse	0	0
Slightly worse	0	0
No difference	1	5
Slightly better	10	53
Significantly better	8	42

100%); after the addition of 3D it was 86%. The 95% CI for the difference in surgeon’s confidence was (30%, 40%), indicating a substantial improvement in the surgeon’s confidence in his surgical plan after viewing the 3D visualization.

In all areas investigated, the cardiothoracic surgeons reported positive benefits to using the 3D visualizations. In all but one case, the surgeons indicated the 3D visualization was clinically helpful. In over two thirds of the cases, the surgical plan was altered due to the 3D visualization, and in all the remaining cases the surgeons still listed items that they understood or appreciated better because of the 3D visualization. When the surgical plan did change, it was often a very significant change. For instance, a heart–lung transplant case with aortic arch reconstruction would not have occurred without the 3D visualization. The surgeon’s case comment was that the “3D visualization was essential. [They] doubt they would have been able to perform the procedure successfully without it—and this information could not have been gotten from the 2D CT. An angiogram might have provided some of the same information.” Similarly, a planned sleeve lobectomy surgery was canceled after the 3D visualization because the surgeons “decided that sleeve lobectomy was not possible because of extensive pulmonary artery involvement by tumor below the upper lobe takeoff.”

Although the radiologists reported fewer and less major changes than the surgeons in their understanding of the case due to the 3D visualization, the changes were still statistically significant. In over half the cases, the radiologists reported improvements in their confidence and understanding. The best measure of how significant the 3D visualization was to the radiologist is whether it affected their radiological report. In over 20% of the cases it changed their report. Figure 2 shows an example still image from a lung

Table 6. Results on how well the anatomy as seen on the 3d visualization correlates with the actual anatomy as seen during surgery by the surgeon

Correlation of 3D with anatomy at surgery	Number of cases	Percentage of cases (%)
Very bad	0	0
Moderately bad	1	5
Ok	0	0
Moderately good	4	21
Very good	14	74

mass resection case, and Figure 3 shows a lung donor airway evaluation case with the preset classification setting emphasizing the main vascular vessels.

Although viewing times were not recorded, in most cases the first 30 s were spent bringing up the study, verifying the correct patient, and checking the initial preset visualizations and fine tuning them as needed. Then the radiologists and surgeon reviewed the case, primarily in the 3D window, but also comparing with the 2D MPR views. The bulk of the time was spent at the end of the session by the surgeon, using the 3D visualization as a model to plan the surgery, and to facilitate communication among the surgery and radiology staff present.

During the study, comments were recorded by the experimenter (BMH), and at the end of the study the physicians were interviewed regarding the use of the 3D visualization as part of their clinical routine. Interviewees included other surgical staff participating in the surgery planning and operation, as well as the lead surgeons and the radiologist. These interviews and analysis of the questionnaires provided several highlights:

- Nonradiologist medical staff seemed to benefit significantly from the 3D presentation. Surgeons, in particular, seemed comfortable using the 3D visualization, perhaps because it

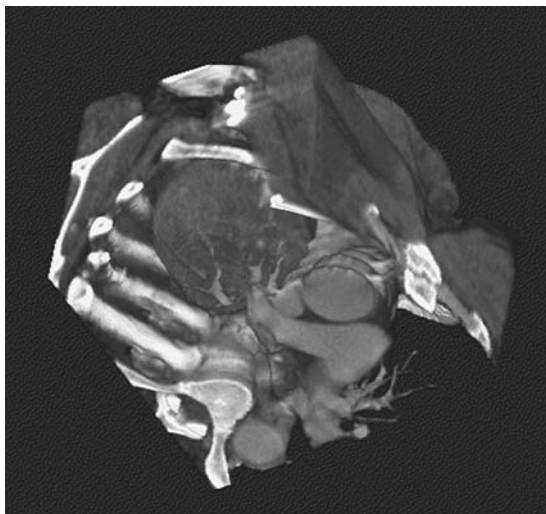


Fig 2. Cranial-caudal view looking up into the right lung, where a large mass resides. SeeThru was helpful in delineating the relationship of the mass to the mediastinum and allowing for planning of the complicated resection.



Fig 3. View from the right side of the patient, with the right (and left) sides of the chest cut away, and the anterior portion of the chest also cut away. The classification is set to emphasize the pulmonary vasculature to help in planning the resection of one lobe of a donor's lung as part of a living related donor lobectomy. The 3D visualization is used to determine the suitability of the left and right lungs for donation (in both vascular, shown here, and airways visualizations).

is closely tied to their clinical experience in seeing and manipulating parts of the body in 3D.

- Experienced radiologists did not benefit as much as the surgeons except for complex or uncommon anatomy. This may be because their extensive training in viewing the 2D films allows them to answer the questions they are expected to address (e.g., is the PA involved or not?), whereas the surgeon has to make detailed technical decisions that benefit from the 3D visualization (e.g., is the involvement of the PA distal enough to permit a resection?).
- In addition to using the 3D visualization for understanding anatomy, the surgeons made extensive use of the 3D representation to communicate with other surgeons and radiologists when trying to understand the anatomy and plan the surgical procedure.
- The typical scenario for using SeeThru to assist in cardiothoracic surgical planning was to classify the volume to the appropriate areas of interest; then cut away and rotate the volume to get the best view; then cut back and forth through the 3D volume to see

interior objects better, especially cutting in and out from an angle similar to the planned surgical entry.

- The ability to conveniently bring up the study immediately after the scan, and see and interact with the study in 3D to visualize information not seen on the 2D slices were reasons the cardiothoracic surgeons gave for using SeeThru.

DISCUSSION

There can be significant variations in the clinical usefulness of 3D visualization depending on the choice of clinical acquisition parameters, the rendering algorithms, and the computer-human interaction methods. With some experience, reasonable choices for these variables can be made. We have found that using real-time volume rendered 3D visualization as implemented in SeeThru, under the interactive control of the clinician, is clinically useful for cardiothoracic surgery planning and diagnostic evaluation in complex cases. The use of such a 3D visualization tool was of clear benefit to the surgeons, who indicated they would use it clinically. In the study, the addition of the 3D visualization was almost always reported to be clinically helpful, and in two thirds of the cases caused the surgeons to change their surgical plan. Further, the surgeons' confidence in their surgical plan improved significantly in almost every case. The radiologists benefited, but to a lesser extent. The radiologists' findings were better comprehended, or sometimes exclusively found using the 3D visualization. Their radiology reports changed 20% of the time due to the 3D visualization.

An important contribution of the 3D visualization that we did not anticipate was its use in supporting the discussion of the diagnosis and planned surgical procedures, allowing a group consensus to be formed while viewing and manipulating the model of the anatomy. These results mesh well with other findings showing real-time 3D visualization to be helpful for surgery planning and diagnostic evaluation. This study demonstrates the positive effect of 3D visualization in cardiothoracic surgery planning, which is a difficult visualization problem because of the small contrast differences in the soft tissue to soft tissue boundaries. These results suggest

that using 3D visualization for complex cardiothoracic surgical planning is of significant benefit, especially to the surgeons, and should be used routinely. From a practical standpoint, it suggests that surgeons should have 3D visualization capabilities on their primary workstation, and that radiologists should have convenient access to their standard picture archiving and communication system (PACS) or a nearby workstation.

FUTURE WORK

SeeThru utilizes both the interactive 3D visualization and the interactive 2D MPR views. Each of these can contribute to the 3D understanding of the anatomy. As most of today's PACS workstations support interactive 2D slices through the scanned volume, but not necessarily interactive 3D visualization, it would be interesting to study how much of the improvement in a combined 3D + 2D interactive visualization could be achieved with only the less expensive, more commonly available 2D-only PACS workstation.

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