Clinical applications of real-time volume rendering

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1. ABSTRACT

Real-time volume rendering of medical image datasets on commercial hardware became possible in 1993. We have developed an application, SeeThru, that allows real-time volume visualization under the interactive control of the physician. This ability enables the physician to look inside of the patients body to visually comprehend the information from radiological procedures, resulting in improved treatment planning. We report on preliminary results from two areas: 1) cardiothoracic surgical planning from spiral computed tomography (CT) and 2) staging of breast cancer from magnetic resonance imaging (MRI). We compared different rendering methods (projection, maximum intensity projection, opacity blended, and opacity combined with gradient blended) and chose opacity blending as the most effective for both applications. In cardiothoracic surgical planning experiment we found the ability to interactively control and view 3D direct volume visualizations resulted in improvements in surgical plans and in the surgeon's confidence in the plan. In the MR breast experiment we found that 3D visualization of the subtraction images improved comprehension and identification of tumor lesions difficult to appreciate on mammograms. Overall, we believe that interactive, real-time volume rendering significantly adds to clinical understanding and improves treatment planning for the patient.

2. INTRODUCTION

Real-time volume rendering of medical image datasets on commercially available hardware has only been possible since 1993. In the past year, several papers have described the technical aspects of how to volume render in real-time on different graphics architectures,[1-11] however, little description has been given to the clinical aspects of how to benefit from real-time volume rendering.

Because some of the terminology used in this paper has different meanings to different specialties and professions, Table 1 gives definitions for certain important terms used in this paper.

> *Real-time*: the computation of a result can be made in real-time (this meaning coming from interacting with the *real* world, that is, where things occur without perceptible delay as seen by the human observer). The major usage of *real-time* in this paper, is that the computer model of the patient's body can be recomputed from the original CT or MRI dataset in *real-time*, or faster than about 10 times a second, so that the observer viewing and manipulating this model on the screen is given the impression she is directly manipulating the object itself.
>
> *Interactive*: The user has interactive control of the visualization, meaning that the user can adjust the parameters that control the visualization in *real-time*. The controls can either be *physical* controls like joysticks or wands, or *virtual* controls like sliders and buttons displayed on the computer screen that are operated by a device like a computer mouse. Examples include rotating the object on the screen, changing parameters to the rendering equations, changing the lighting conditions, or using a cut plane to cut out portions of the volume.
>
> *Volume Rendering*: Classification of exactly what constitutes surface rendering versus volume rendering is still considered an open subject of debate by some in the field. I will use the term volume rendering to refer to any method that directly renders the output visualization from the original volume data, without resorting to the intermediate step of representing the volume as any particular surface or set of surfaces. Examples of surface

rendering includes methods like isosurfaces or polygonization via Marching Cubes[12] or similar algorithms. Examples of volume rendering methods include summing projection, maximum or minimum intensity projection, and blending methods like opacity and/or gradient based algorithms.[5,8,13,14,15]

Table 1. Definition of terms used in this paper.

We have conducted two pilot experiments in the Radiology department at the University of North Carolina at Chapel Hill, using our SeeThru rendering application, to test the clinical merit of real-time volume rendering. The first experiment was using real-time volume display of spiral chest CT studies to help cardiothoracic surgeons plan operations. Cardiothoracic studies were chosen because visualization of the soft-tissues, especially in the chest, have presented significant difficulties in the past. This is because previous work has been limited mainly to anatomy easily defined via thresholding to obtain a surface, or by maximum intensity projection (MIP) rendering to see bright areas of contrast inside of vessels. Soft-tissue objects on the other hand, are difficult to classify and segment because the densities of different soft-tissue objects overlap one another. The second experiment was using real-time volume display of breast MR studies to enhance the visibility of breast lesions and silicone implant abnormalities. This area was selected because of its promise in improving visualization of breast cancer in women with a high risk of the disease.

3. BACKGROUND

3.1 Real-time 3D Medical Volume Visualization

Static 3D images or precomputed cine loops (rotations of an object around a single axis) have been available for many years, however, they have not been widely used in clinical practice, except for bone reconstruction (shaded surface display,[16,17] radiation therapy treatment planning,[15] and recently in work in CT and MR angiographic studies (maximum intensity projection).[18,19] A good summary of the state of the art in 1991, prior to real-time volume rendering, is given by Udupa et al.[20]

One reason for this lack of acceptance is that previous methods have required preprocessing steps. Generally, they are available only after a significant time delay, and require experienced personnel to control the preprocessing. I believe the next significant step will be the change that occurs when daily clinical studies are viewed interactively in real-time using a single visualization combining 2D and 3D. A direct volume visualization would be available immediately after the scan is completed because no pre-processing steps are required. This combined with the ability to perform the CT reconstruction of the entire study within a few seconds of completing the scan (see, for instance, description by Cabral et al.[7] for standard CT reconstructions) means that physicians will be able to see the study in 2D and 3D before the patient has left the scanner. And, factoring in the fast communications networks like the information highway, you will be able to display the study to a colleague on the other side of the globe to consult about the case before the patient has left the room.

Besides making the study immediately available, I have previously described three significant benefits of real-time, interactive visualization compared with static or precomputed 2D visualizations.[10] These are:

- Arbitrary viewpoint,
- Cutting away,
- Modifying visualization method.

Currently the way radiologists and physicians understand a 3D volume is by viewing a static image or collection of images that represent an object or a set of slices through an object. This is analogous to a still *photograph* of an object of interest.

Arbitrary viewpoint

By this I mean the ability to view the volume from any orientation and distance. The *arbitrary viewpoint*, as opposed to the *photograph* , is analogous to putting the object in your hands and letting you rotate it to view from any angle, and to hold it closer or farther away. The biggest inherent advantage is the increased 3D spatial understanding of the object from the kinetic depth effect that occurs when the observer rotates the object. Another significant advantage is being able to search out the optimal view or set of views to answer a clinical question.

Cutting away

Cutting away allows the observer to cut into an object to see its interior. It can also be used to remove portions of the object that may be occluding other areas of interest. This is analogous to letting the observer be the pathologist and cutting any arbitrary portion of the volume away with a magic knife to see inside.

Modifying visualization method

This means that the observer can choose how the object is visualized by interactively changing the method, and the parameters to the method, that are used to calculate the visualization. This is analogous to playing with the laws of nature in order to change the way we perceive the object. We may wish to make changes in the viewing environment or in the object itself. For instance in the viewing environment, we might change the amounts of ambient light versus specular reflection, or the number and position of light sources. With regard to the object itself, we may redefine its properties of reflection, emission and absorption of light. For example, we might choose to have certain tissue types be transparent, while other tissue types are colored specific hues when seen in a dark room illuminated by several spotlights.

Thus, having the ability to select arbitrary viewpoints and to cut away portions of the volume moves us beyond still photography of objects, to having the object in our hands and being able to view the whole or any interior portion of the object. Control of the visualization method allows exploration and fine tuning of the visualization in order to maximize the observer's understanding of the anatomical structures or metabolic functions of the patient.

3.2 Visualization method and parameters

The Seethru@ application at the University of North Carolina Department of Radiology, was specifically developed to meet the three needs outlined in the last section. In addition to providing a real-time 3D volume visualization on the computer screen under interactive user control, it also provides 2D multi-planar reformat windows so that the clinician can view 2D slices from arbitrary angles through the volume. Thus, the aim of SeeThru is to provide an natural, easy to use 2D and 3D interface to the radiological study. SeeThru is more completely described by Hemminger et al.[10,11]

In our pilot cases, we tried each visualization algorithm and many thousands of different parameter choices to those algorithms (the large number of choices were possible because they were under interactive control). We found that opacity rendering far outperformed the other methods provided in SeeThru (X-ray projection, MIP, and gradient). The projection X-ray method, while having the benefit of appearing like an X-ray, is limited by not providing good 3D surface definition. The MIP algorithm, is limited by discarding 3D spatial information and only representing the brightest spots in a specific projection. While this is effective for causing contrast inside of vessels to highlight and be easily visible it is not as useful as opacity blending for more general problems. We initially expected the gradient method to perform well. While the gradient methods were effective in visualizing bone and obvious surfaces, gradient values were too noisy when trying to visualize soft-tissues areas, and this resulted in very noisy surface appearances in the images. The gradient method might improve somewhat when true light sources are modeled, as the current implementation supports only a single light source fixed with respect to the object. The clear favorite was opacity based blending, where the density value in the study is used both for the opacity value and the alpha blend value. This was due in a large part to the ability to interactively control lookup tables modifying the opacity and alpha values, allowing the user to select most any surface in the volume to visualize.

3.3 CT scanning and reconstruction

A combination of factors have resulted in higher quality volume datasets acquired on the CT scanners. 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.[18,21,22] Finally, administration of intravenous (IV) contrast material enhances the contrast difference between vessels of interest and surrounding tissues. When performing spiral CT of the thorax, the amount of IV contrast can be reduced.[23] Spiral CT studies with contrast are now standard practice in our department. For the thoracic cases the protocol used was 90 to 120 ml Omnipaque 300 administered via power injector through the antecubital vein at 2 to 3 ml/sec. Scanning was begun approximately 20 seconds after initiation of contrast administration.

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 normal radiation dosage. Based on our prior experience and other's work,[21] 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.

3.4 MR scanning and reconstruction

Previous Work

MR of the breast is still being investigated as a tool to use to evaluate breast abnormalities. Intravenous administration of Gadolinium-DTPA (Gd-DTPA) allows visualization of tissues with an increased vascular supply (i.e. tumor). Much work has been done to define optimal pulse sequences.[24-27] The currently favored method with Siemens equipment is the 3D FLASH (fast low-angle shot) sequence, which excites a volume of tissue so that images can be reconstructed in three dimensions. With this sequence, fat has a bright signal, as do enhancing lesions. Unless lesions are large, they can be difficult to detect with the unaided eye. Computer subtraction techniques (post-enhancement signal minus pre-enhancement signal) are helpful in detecting the presence of lesions.

Breast registration between scans of a single study

One issue we were concerned about was whether the images would be registered well enough between successive scans of the breast so as to not cause artifacts on the digital subtraction. Registering a fairly fluid object like the breast can be a difficult task, and is currently under investigation. For our study, we choose not to try to register the multiple scans. During work leading up to the study, we found it easy to visually assess misregistrations on the 3D subtraction visualization, as misregistered studies display obviously false surfaces on areas like the skin edge which would have had no Gd-DTPA take-up. Due to good technique and patient cooperation, we did not have to eliminate any scans from the study due to misregistration.

4. METHODS

4.1 Cardiothoracic surgical treatment planning

We have evaluated 14 cases for cardiothoracic surgical planning including tumor removal (n=5), heart/lung transplantation (n=3), airway stent placement (n=3), repair of congenital heart defects (n=1), aortic aneurysm (n=1), and resection of pulmonary arteriorvenous malformation (n=1). Images were acquired on a Siemens Somatom+ spiral CT scanner, using single breath hold spiral acquisitions with contrast. Contrast was given as described in section 3.3. 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 mm/sec; the second number is the acquisition slice thickness in mm; and the third number is the reconstructed thickness in mm. All studies are 512x512 pixels in each individual slice.

Each study volume was reconstructed for optimal 3D visualization in real-time under the interactive control of the physician and presented on the computer screen, using our SeeThru display application running on an SGI Crimson Reality Engine computer system with two RM5 raster manager boards. The radiologist and primary attending surgeon who performed the operation filled out a questionnaire form after each operation. Multiple interviews were conducted with each of the involved radiologists and primary attending surgeons, during the experiment and at the conclusion of the experiment, to help in evaluating strengths and weakness of the 3D visualization.

Prior to this study we piloted the same methods on 4 patient cases from the cardiothoracic clinic. Once the study began, we asked the cardiothoracic surgeons to simply bring us cases from their clinic. There was no pre-selection of patients, and all studies were included except for one patient who changed her mind and elected not to have surgery.

4.2 MR breast cancer staging and evaluation

We have processed 13 MR breast studies, of patients selected because of suspected breast masses (either palpable or mammographically detected, n=10), or patients with a clinical question of a silicone implant rupture (n=3). For the patients with suspected breast masses, the purpose was to evaluate whether real-time 3D visualization of the MR study was helpful in evaluating the extent of enhancing breast lesions, or in screening for other foci of cancer in the breasts. For the patients with possible implant ruptures, the purpose was to evaluate the extent or existence of implant ruptures. For both sets of patients, the comparison was between the 3D (with and without subtraction) presentation and the standard presentation on mammograms and standard film MR. Patients were recruited by the radiologists based on suspicious mammographic findings and physical findings.

The MR studies were dynamic 3D FLASH volume acquisitions performed on our Siemens Magnetom 1.5T MR. A single pre Gd-DTPA scan and three post Gd-DTPA contrast scans were acquired. The acquisitions were coronal 3D FLASH with TR=12, TE=5, and flip-angle=25°. Contrast was given in a bolus injection of 0.1 mmol per kg. The Siemens dedicated breast coil detector was used. Each of the post contrast scans were acquired in 75 seconds, with the first scan beginning immediately after injection of the Gd-DTPA contrast. In addition to the normal pre and post images, digitally subtracted volumes (first post contrast minus pre contrast) were viewed using SeeThru. The volumes were 256x256 pixels per slice, with 64 slices, although only 256x150 pixels per slice contained image information. The digital subtractions were done without any correction for misregistration between acquisitions. The radiologists completed questionnaires after each study.

5. RESULTS

5.1 Cardiothoracic surgical treatment planning

Results were tabulated for each of the questions on both of the radiologist's and surgeon's forms. The average values are given below in Tables 2 and 3, for the surgeons and radiologists, respectively. Fourteen cases are reported for the radiologists, while only thirteen cases are reported for the surgeons because one patient has elected to not pursue surgery at this time.

Did the 3D visualization change your surgical plan?
69% (9/13) Yes
31% (4/13) No

My confidence in our surgical plan changed from 47% *to* 85% *after using the 3D visualization.*

How well did the 3D visualization correlate with what you saw in surgery?
0% (0/12) very bad match
0% (0/12) moderately bad match
0% (0/12) OK
25% (3/12) moderately good match
75% (9/12) very good match

Was the 3D visualization clinically helpful based on the surgery?
0% (0/12) made significantly worse
0% (0/12) made slightly worse
0% (0/12) made no difference
50% (6/12) made slightly better
50% (6/12) made significantly better

Table 2. Each reported value is the average of all the cases included in the study. In one case the surgery was not performed after the 3D visualization showed it not to be feasible. No answers were reported for this case for the last two questions because they involved the relationship of the 3D visualization with the surgery, which was not performed.

In all areas investigated, the cardiothoracic surgeons reported positive benefits to using the 3D visualization. In over two thirds of the cases the surgical plan significantly changed, and in all the remaining cases the surgeons still listed items that they understood or appreciated better after the 3D visualization. And, when the surgical plan changed, it was often a very significant change. For instance, in one case they would not have operated had not the 3D visualization been used, and in another, surgery was canceled after the 3D visualization showed it to not be feasible. Using the 3D visualization for surgical planning is of significant benefit to the surgeons, and should be used routinely.

Percentage of cases where the understanding of the case was
0% (0/14) worse because of seeing the 3D
43% (6/14) no different because of seeing the 3D
36% (5/14) better because of appreciating additional information regarding things already seen on 2D
21% (3/14) better due to seeing something seen exclusively on the 3D visualization

Was the 3D visualization helpful in your understanding the case?
0% (0/14) made worse
43% (6/14) made no difference

36% (5/14) made slightly better
21% (3/14) made moderately better
0% (0/14) made significantly better

Was the 3D visualization helpful when conveying your understanding of the case to the surgeons?
0% (0/14) made worse
21% (3/14) made no difference
29% (4/14) made slightly better
29% (4/14) made moderately better
21% (3/14) made significantly better

Did the 3D visualization change your radiology report?
21% (3/14) Yes
79% (11/14) No

Table 3. Summary of data from radiologist's score sheets for each surgery. Each reported value is the average of all the cases included in the study.

While the radiologists reported fewer and less major changes than the surgeons in their understanding of the case due to the 3D visualization, there were still significant results. First, in over half of the cases the radiologists reported improvements in their confidence and understanding. Second, perhaps the best measure of how significant the 3D visualization is to the radiologist, is whether it would affect a change in their dictated radiology report; in over 20% of the cases it changed the report. Figure 1 shows an example still image from a lung tumor mass resection case, and Figure 2 shows an lung donor airway evaluation case.

Figure 1. A large tumor mass can be seen in patient's right lung field on the left side of picture (arrow pointing at mass). Note that the visualization is able to show detail on all areas of interest including bone, vessels, and tumor mass. The front and side of the chest were cropped away to reveal the tumor mass.

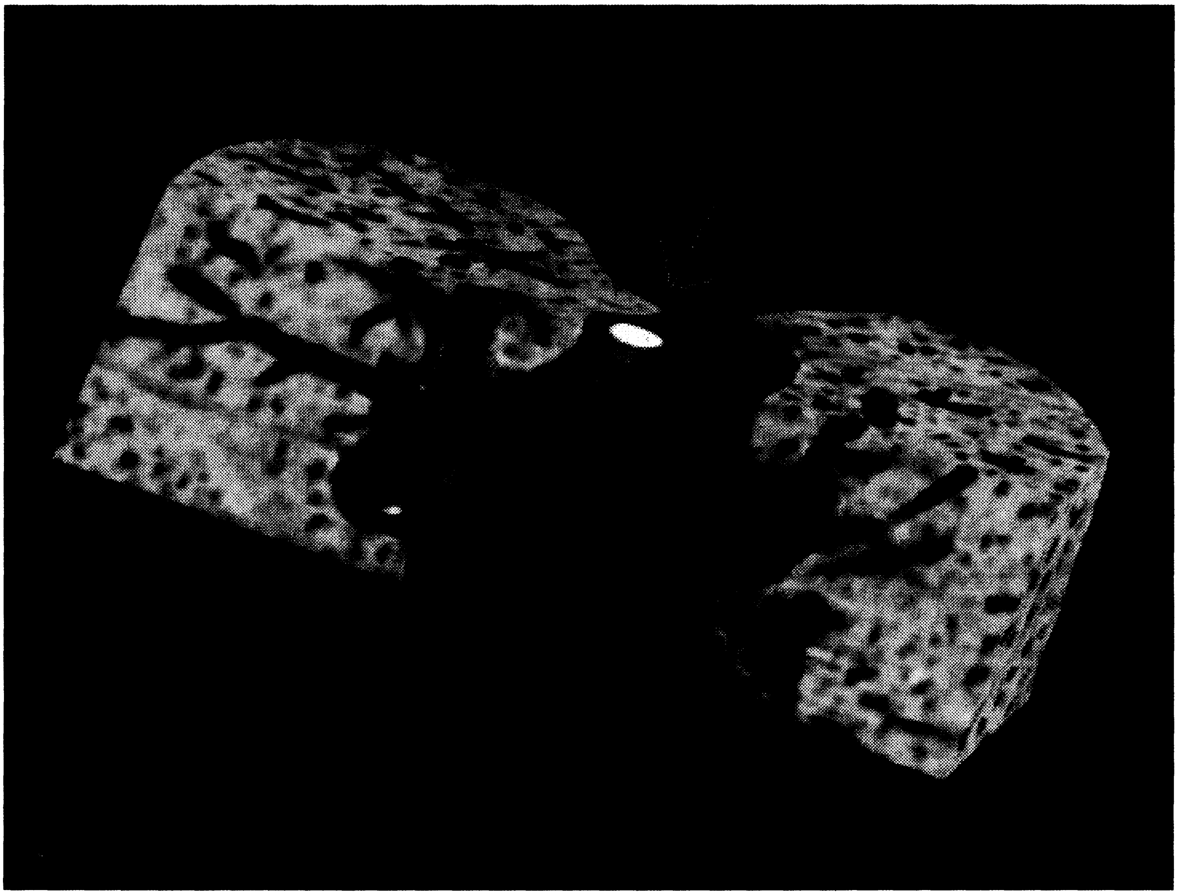

Figure 2. This is a visualization of a normal airway, shown viewed from the front of the patient with part of the frontal area of the chest cut away to reveal the interior portion of the lungs. The arrow points down into the top of the airway, just before it branches into the separate lungs. The patient had normal lungs, and was being evaluated for suitability as a lung lower lobe donor. The rendering parameters for this image are "reversed" from those in Figure 1; i.e. areas that are dark on this CT (airways) were visualized as bright objects, while normally bright objects (vascular structures in lungs) are rendered as dark.

5.2 MR breast cancer staging and evaluation

Breast Lesions

Results were tabulated for all the lesion cases, and are summarized in Table 4. The radiologists reported improvement because of the 3D visualization in 80% of the cases (10% exclusive to 3D plus 70% additional information in 3D). Most importantly, their MR report would change in half the cases based on being able to see the 3D visualization. Such a significant change suggests that all MR breast protocols should include subtraction with 2D and 3D visualization. Figure 3 shows an example MR breast case where the lesion and vascular structures are readily apparent. This lesion could not be seen on the mammogram because it was adjacent to a breast implant in the patient.

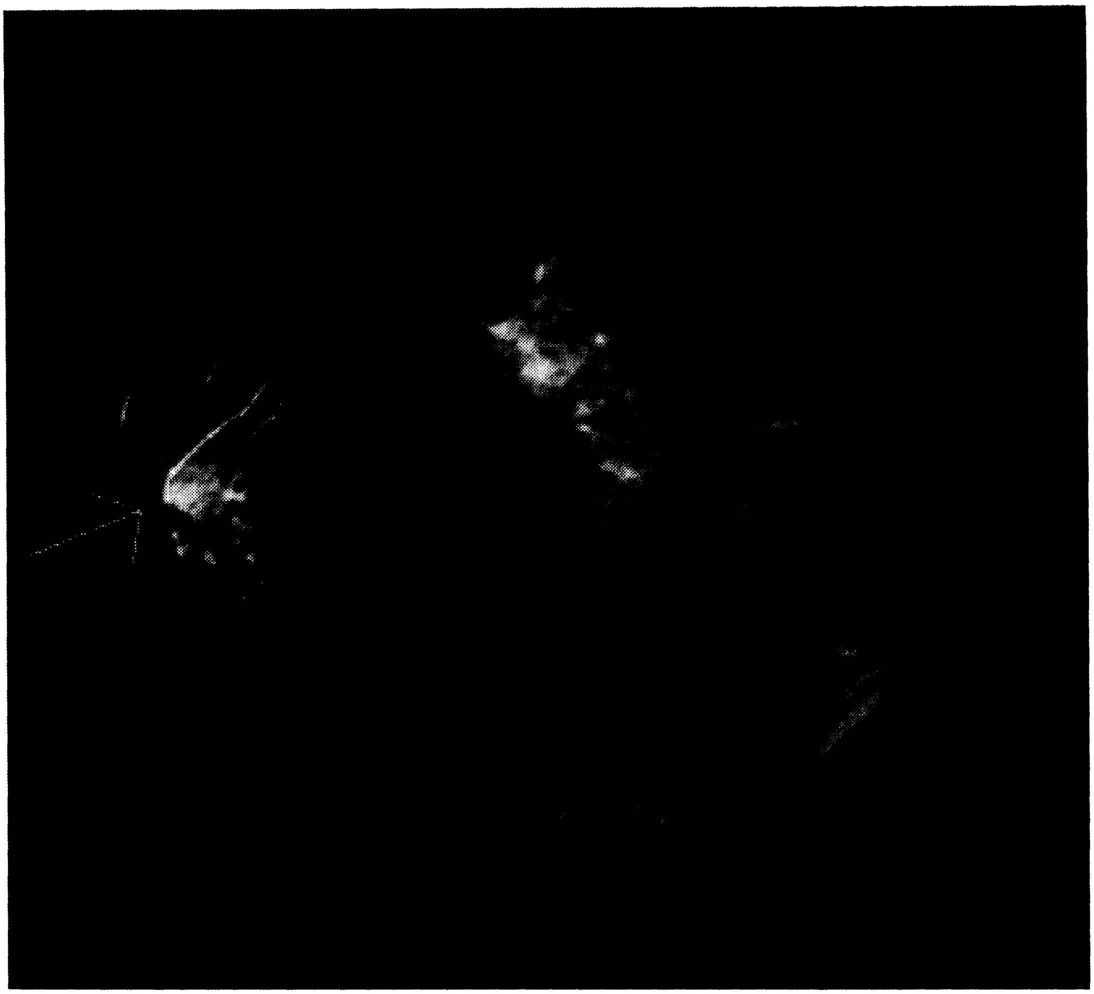

Figure 3. Example MR Breast lesion study. The arrow is pointing at the lesion (seen as bright round object). The visualization shows the patient viewed from the front upper left, with the patient's right breast on the left side of the picture. The vascular structures are also easily seen, with increased vascular activity feeding the tumor area. The object in the middle back is the front portion of the heart. On the left breast there is evidence of slight misregistration on the outermost skin surface.

Percentage of cases where the understanding of the case was
0% (0/10) worse because of seeing the 3D
20% (2/10) no different because of seeing the 3D
70% (7/10) better because of appreciating additional information regarding things already seen on 2D
10% (1/10) better due to seeing something seen exclusively on the 3D visualization

Rate confidence in understanding before 3D visualization 82% *and after 3D visualization* 91%.

Did having the 3D visualization provide significant additional benefit in understanding the case?
0% (0/10) made worse
20% (2/10) made no difference
50% (5/10) made slightly better
30% (3/10) made moderately better
0% (0/10) made significantly better

Did the 3D visualization of the subtraction improve your comprehension of the tumor?
0% (0/8) made worse
50% (4/8) made no difference
38% (3/8) made slightly better
12% (1/8) made moderately better
0% (0/8) made significantly better

Did the 3D visualization change your MR radiology report?
50% (5/10) Yes
50% (5/10) No

After the 3D visualization would you change your mammography radiology report?
30% (3/10) Yes
70% (7/10) No

Table 4. Note that the added information, referred to as "3D" or "3D visualization" consisted of using SeeThru showing 2D plus 3D views of original and subtraction datasets presented on a computer monitor, under interactive control of the user. On the fourth question, two cases were ranked *Not Applicable* and excluded from the scoring because the 3D subtraction visualization showed no tumor present.

Implants

Because we had difficulty differentiating between silicon implant leakage density values from those of surrounding parenchyma, we did not pursue this after the initial three implant cases. We are continuing to refine the MRI acquisition technique in hopes of being able to better differentiate silicon leakage of the implant from breast tissue at fine spatial resolutions.

5.3 Highlights learned from data analysis and interviews

- Surgeons benefited significantly from the 3D visualization. Experienced radiologists did not benefit as much as the surgeons except for complex or uncommon anatomy, as they are well trained at reconstructing the expected anatomy in 3D from 2D cross sections. In the MR breast study, the radiologists indicated more benefit from the 3D as compared with the cardiothoracic study. This was probably because they did not have previous experience seeing the 3D FLASH subtraction volumes, and without the practice of constructing a mental mode of the 3D anatomy in their head, found the 3D visualization was more helpful to them.

- Non-radiologist medical staff, without significant experience at reconstructing 3D from 2D slices, seem to benefit significantly from seeing and interacting with the 3D visualization. Surgeons seemed to be especially comfortable using the 3D visualization tools, perhaps because it is closely tied to their clinical experience in manipulating the true 3D objects (i.e. the patient's body).

- In addition to using the 3D visualization for understanding the anatomy, the surgeons made significant use of the 3D representation as a model to communicate with other surgeons and medical staff in planning the operation.

- The typical scenario using SeeThru to assist in cardiothoracic surgical planning was to classify the volume to see appropriate areas of interest; then to 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.

- 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 2D slices, were the reasons the cardiothoracic surgeons gave for using SeeThru.

- One of the major benefits of the MR SeeThru presentation was that it significantly reduced the number of images presented. The radiologist interacted with four images in the SeeThru application (a 3D volume image, and three multiplanar slice reformats from any position on each of three orthogonal axes of the study). This compares very well with trying to comprehend these same slices as printed on film, where the radiologist would have to sort through and compare 256 individual images. The 3D subtraction was especially effective in reducing the volume of information down to its essence in a single 3D volume view.

6. CONCLUSIONS

There are significant variations in the clinical usefulness depending on the clinical acquisition methodology, the rendering algorithms used for the 3D visualization, and the computer human interaction methods used for the visualization. With some experience, reasonable choices for these parameters can be made. We have found that using real-time 3D visualization, under the interactive control of the clinician is clinically useful for cardiothoracic surgery planning and MR breast evaluations with suspected masses. The cardiothoracic surgeons changed their surgical plan in over two thirds of the cases after using the 3D visualization, and in several cases changed their mind regarding whether to attempt a surgery based on the 3D visualization. While the radiologists appeared to benefit less than the surgeons, they still reported significant gains. In the cardiothoracic study the radiologists showed gains in appreciating the study in 50% of the cases, and changed their report in 20%. In the MR breast study, the radiologists reported benefits in using the 3D in 80% of the cases and changed their reports in 50% of the cases.

7. FUTURE WORK

Both of these experiments are preliminary results. In the case of both the cardiothoracic and MR breast lesion studies we believe the work is worth continuing. We have recently received funding to pay for the acquisition of 100 more MR breast cases at our institution. We are currently adding to the cardiothoracic cases and awaiting new funding. We expect to conduct a cardiothoracic study on the order of 60-100 patients over the next three years. We have postponed work on evaluating implant ruptures until we are better able to distinguish the silicone implant material from breast tissue. We are also beginning work in applying the 3D visualization to many other clinical areas, primarily including visualizing vessels in the abdomen, and the head and neck.

8. ACKNOWLEDGMENTS

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