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Real Time 3-Dimensional Ultrasound for Guiding Surgical Tasks

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ABSTRACT Objective: Two-dimensional ultrasound (US) can only guide basic interventional tasks due to limited spatial orientation information offered by this imaging modality. High resolution real time 3-D US can potentially overcome this limitation thereby expanding the applications for interventional US. The following study examines the benefits of real time 3-D US in performing both basic and complex image-guided surgical tasks.

Materials and Methods: Seven surgical trainees performed three tasks in an endoscopic testing tank using 2-D US, biplanar 2-D US, and 3-D US for guidance. Surgeon-controlled US imaging was also tested. The evaluation tasks were (1) Bead-in-Hole Navigation, (2) Bead-to-Bead Navigation, and (3) Clip Fixation. Performance measures included completion time, tool tip trajectory, and error rates with endoscope performance serving as a control measure for each subject.

Results: Compared to 2-D US guidance, completion times decreased significantly with 3-D US for both Bead-in-Hole Navigation (50%, p=0.046) and Bead-to-Bead Navigation (77%, p=0.009). Furthermore, tool tip tracking for Bead-to-Bead Navigation demonstrated greater navigational accuracy using 3-D US vs. 2-D US (46%, p=0.040). Biplanar 2-D imaging and surgeon-controlled 2-D US did not significantly improve performance vs. conventional 2-D US. In real time 3-D mode, surgeon-controlled imaging and changes in 3-D image presentation by adjusting the perspective of the 3-D image did not diminish performance for Bead-to-Bead Navigation. For Clip Fixation, completion times proved excessive with 2-D US guidance (> 240 s); however, with real time 3-D US imaging, completion times and error rates were comparable to endoscope-guided performance.

Conclusions: Real time 3-D US can guide basic surgical tasks more efficiently and accurately than 2-D US imaging. Real time 3-D US can also guide more complex surgical tasks which may prove useful for procedures where optical imaging is suboptimal as in fetal surgery or intracardiac interventions.

Key words: Image-guided intervention, instrument tracking, minimally invasive surgery,
3-D ultrasound

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INTRODUCTION

For medical diagnosis, ultrasound (US) imaging offers advantages of good soft tissue resolution, portability, and applicability in a wide range of clinical settings with minimal expense.[1,2] Ultrasound has also been used to guide a variety of interventional procedures including tumor biopsy and abscess drainage[3] with very few procedure-related complications.[4] However, with current US systems, these procedures are limited to those where a rigid tool (e.g. a core biopsy needle) can be guided to a remote target by keeping both the target and the tool tip in the imaging plane at all times.[2,5]

To expand the number of clinical applications for US-guided interventional procedures, investigators have used several approaches to overcome the limitations inherent in 2-D imaging. These include integration of 2-D US images into a 3-D augmented reality operative scene[6] and use of a robotic arm for computer-assisted positioning of a biopsy needle under US guidance.[7,8] Unfortunately, these approaches require additional equipment which detracts from the flexibility, portability, and reduced expense which US imaging offers over CT or MRI-guided interventions.

Surgeon-controlled US (ultrasound imaging performed by the surgeon rather than by a sonographer) has become increasingly popular and represents another possible approach to overcoming the limitations of 2-D US for image-guided interventions.[9,10] Theoretically, navigational accuracy is enhanced by improving the surgeon's intuition for the alignment of the surgical tool with the operative target shown in the US image of the surgical field.[11] However, the advantages of surgeon-controlled interventional US have not been conclusively demonstrated.

Three-dimensional US imaging has great potential for interventional applications.[12,13] However, acquiring and rendering 3-D US images with the resolution and frame rate required for guiding procedures has proven quite challenging.[14-17] Current 3-D US systems combine specialized acquisition methods with off-line image processing to produce a 3-D image. Consequently, although these imaging techniques may offer additional spatial orientation information, imaging time lags have limited their use to diagnostic[18,19] and surgical planning applications.[20]

This paper reports the use of a new 3-D US system (Philips Medical Systems, Andover, MA) for guiding surgical tasks inside a testing tank. Details of this system are presented below along with a preliminary validation study designed to explore the merits of using real time 3-D US for performing image-guided interventions. The results of this study then lead to several conclusions regarding future clinical uses for this technology.

MATERIALS AND METHODS

Imaging System

The imaging system employed for this study consists of a novel US transducer along with a custom image processing and rendering platform (Philips Medical Systems, Andover, MA). The imaging probe is a hand-held transducer containing approximately 3,000 active piezoelectric crystal elements arranged in a fully-sampled 2-D array. The current 4 MHz transducer has a lateral resolution of 1.7±0.4 mm when used to image 4 mm diameter glass beads at a distance of 10 cm in the testing tank described below.

The image processing and rendering platform is based on a dual 2.2 GHz Pentium 4 processor PC which supports multiple imaging modalities including conventional B-mode 2-D US, 2-D color flow Doppler imaging, biplanar 2-D US (i.e. orthogonal 2-D images displayed side-by-side), and several real time volume rendered modes. These volume rendered modes are based on traditional ray-casting methods where the opacities encountered by each sonographic "ray" are blended to yield the opacity of an individual pixel, $P(r)$ given by Equation (1):

$$P(r) = \sum_{k=0}^{K} [c(r,k)\alpha(r,k) \prod_{i=k+1}^{K} (1-\alpha(r,i))] \qquad (1)$$

where $c(r,k)$ is the shade value and $\alpha(r,k)$ is the opacity value for each k^{th} voxel along the r^{th} ray.[21]

The sonographer can adjust the presentation of the US image by toggling between various imaging modes. In addition, a trackball on the system console permits adjustment of the orthogonal slice location in biplanar mode and arbitrary rotation of the image in 3-D mode. The frame rate for all imaging modes ranges from 20-25 frames per second (fps).

For this study, a custom tank was prepared for evaluating surgical task performance under simulated clinical image-guidance conditions. This tank consists of a plastic reservoir covered by an opaque dome through which surgical instruments are inserted. The bottom of the tank is lined with an acoustic polymer (Sylgard 170, Essex Brownell, Edison, NJ) mixed with Ni powder (Atlantic Equipment Engineers, Bergenfield, NJ) and microballoons (Potters Industries Inc., Carlstadt, NJ). Degassed double de-ionized H_2O serves as the imaging medium inside the testing tank.

Study Design

Seven surgical trainees with experience in minimally invasive endoscopic surgery were recruited for this study (average surgical training=4.6 years). Each subject performed three endoscopic surgical tasks inside the testing tank guided by endoscopic imaging, 2-D US, and 3-D US. In addition, biplanar 2-D US, surgeon-controlled US, and rotated 3-D images were also tested on one of the surgical tasks. After three practice attempts with each

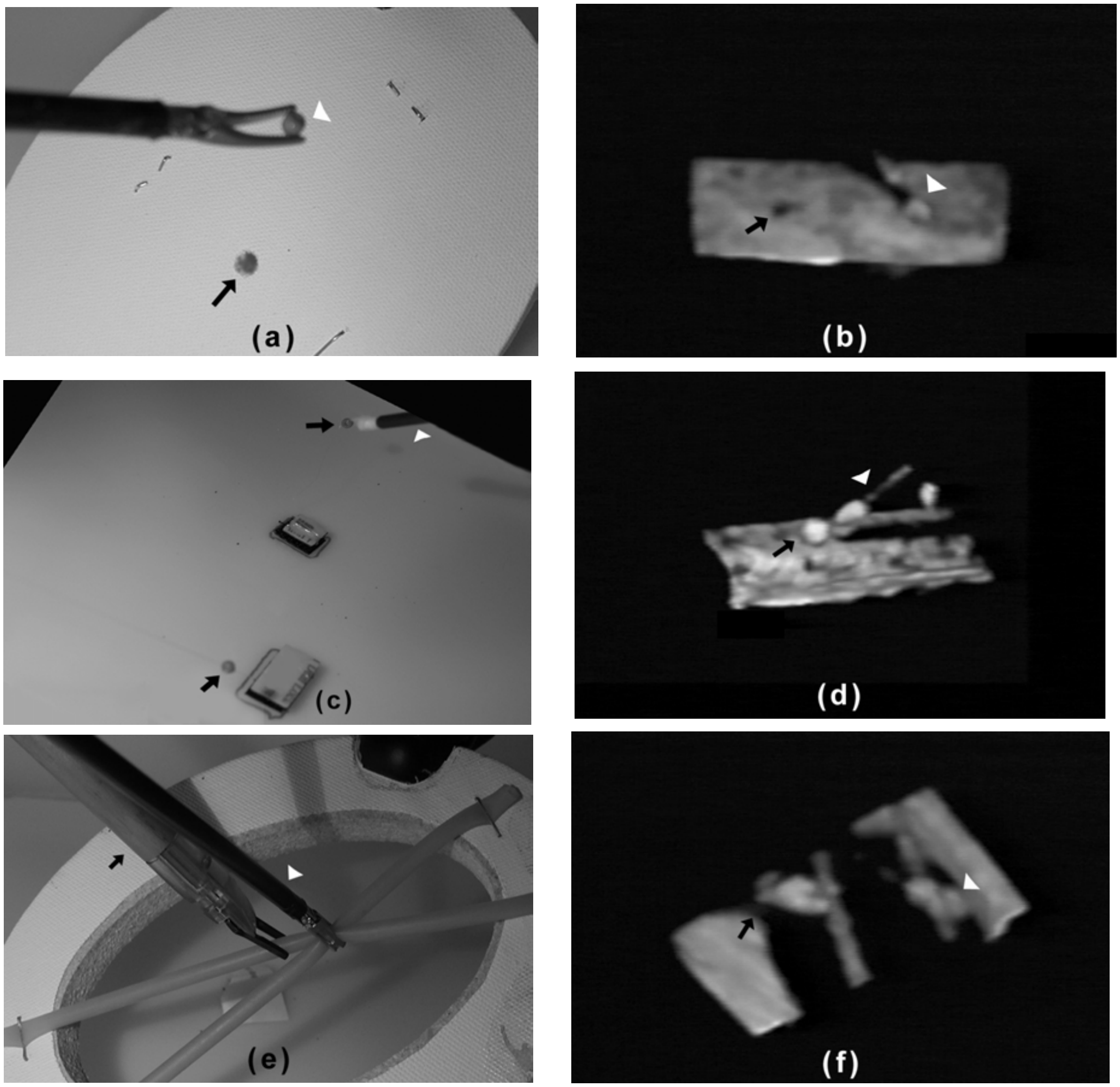


Fig. 1. Optical images of the evaluation tasks with associated real time 3-D US images. (a, b) Bead-in-Hole Navigation involving placement of a glass bead (arrowhead) through a pre-cut hole in a planar surface (black arrow). (c, d) Bead-to-Bead Navigation of a blunt surgical probe (arrowhead) between two glass beads (black arrows) suspended within the US testing tank. (e, f) Clip Fixation where a grasper (arrowhead) is used to approximate adjacent tubes which are then anchored together with a clip application device (black arrow).

imaging modality, subjects performed the task under endoscope guidance which was used a performance normalization factor for each subject. A Latin squares scheme was used to randomize the order of US image presentation to avoid a learning bias in the task performance data set. All images aside from surgeon-controlled imaging were obtained by the same sonographer (JAS) using appropriate interventional US imaging techniques.[5]

The three surgical tasks were Bead-in-Hole Navigation, Bead-to-Bead Navigation, and Clip Fixation. The first task required subjects to place a 4 mm diameter plastic bead into a 5 mm hole in a canvas sheet (Fig. 1a, b). Starting with a plastic bead in the jaws of a standard endoscopic grasper (Ethicon Endosurgery, Cincinnati, OH), the tool was positioned approximately 6 cm from the target hole on the perimeter of an oval frame suspended in the testing tank. With both the tool and target hole in view on the US system screen, subjects attempted to insert the bead through the hole. This task was used to demonstrate feasibility; thus, only 2-D vs. 3-D US completion times were measured.

Bead-to-Bead Navigation (Fig. 1c, d) tested the ability of subjects to navigate between two objects without any constraints on the tool tip. Two plastic beads were suspended inside the testing tank 6.3±0.3 cm apart, and a blunt surgical tool was used to navigate between them. All subjects started with the tool tip touching the bead closest to their dominant hand and then attempted to move the tool tip to the target bead as quickly and directly as possible. Subjects completed this task using 2-D US, biplanar 2-D US, 3-D US, and surgeon-controlled US (2-D and 3-D). In addition, modified 3-D views were evaluated. This modified 3-D presentation involved rotating the image "backwards" to give the operator a more horizontal view of the beads (15° view) or rotating the image "forward" to a more vertical perspective (75° view).

Finally, Clip Fixation (Fig. 1e, f) is a common surgical maneuver used to anchor a repair patch in place or to fix adjacent tissues to one another during reconstructive surgery. Starting from a peripheral location on the task frame, subjects maneuvered a grasping tool and an endoscopic clipping tool (Ethicon Endosurgery) into the US field where two adjacent 5 mm diameter surgical tubes were held in view by the sonographer. Subjects then approximated the adjacent tubes with the grasper and fixed them together with a metal clip.

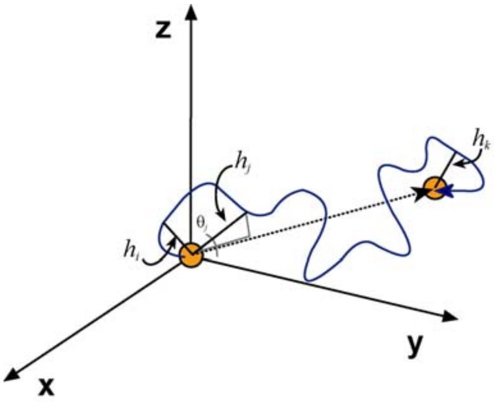
Task performance measures were completion times (measured by an observer viewing the task through an endoscope), mean and maximum deviation from a straight-line path (Bead-to-Bead Navigation), and misapplied clips (Clip Fixation). Tool tip trajectories were measured with an electromagnetic tracking device (Flock of Birds, Ascension Technologies, Burlington, VT) fixed to the handle of the surgical instrument. Using the nomenclature of Fig. 2a, mean deviation, D_{mean}, and maximum deviation, $D_{\max}$, from a straight-line path were then calculated with the following equations:

$$D_{mean} = \frac{1}{n}\left(\sum_i h_i + \sum_j h_j \sin\theta_j + \sum_k h_k \right) \qquad (2)$$

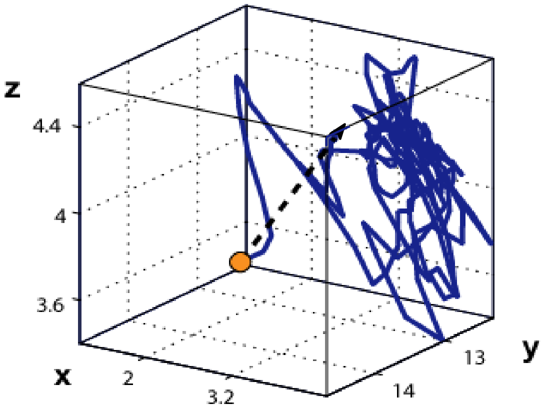
$$D_{\max} = \max_{i,j,k}\{h_i, h_j \sin\theta_j, h_k\} \qquad (3)$$

Here h_i, $h_j \sin\theta_j$, and h_k represent minimum distance vectors from the straight-line path between the beads to each acquired data point along the tool tip path where the latter consists of n data points. Typical paths for both 2-D and 3-D US guidance are shown (Fig. 2b and c, respectively).

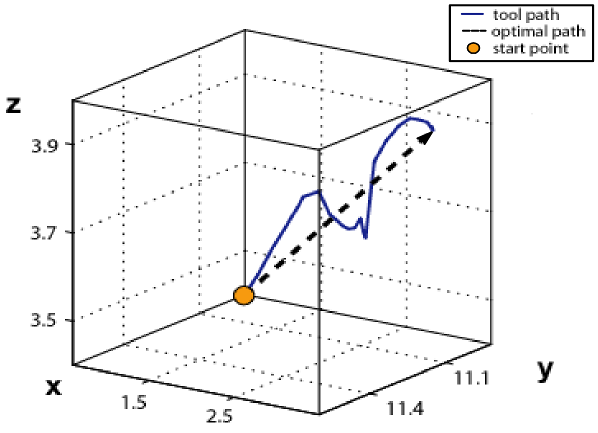
For Clip Fixation, the task was considered complete when a secure fixation clip had been applied across both



(a)



(b)



(c)

Fig. 2. Tool path deviation measurement. (a) Illustration of deviation distance. Spheres represent glass beads from the Bead-to-Bead Navigation task with the ideal linear path indicated by a dashed line. The solid line is a graphic representation of a tool tip path. (b) Typical path for task completion using 2-D US guidance. (c) Typical path for task completion using real time 3-D US guidance.

tubes. Errors were defined as a clip applied incorrectly to a single tube thereby failing to successfully approximate the two tubes. In the event of a misapplied clip, subjects were instructed to continue attempts to approximate the tubes until the task was completed successfully.

Statistical Analysis

Comparisons of all task performance measures between US imaging modes were made using a paired one-tailed Wilcoxon signed rank test (SPSS 10.1, Chicago, IL). For all comparisons, $p \leq 0.05$ was considered statistically significant.

RESULTS

Completion times for Bead-in-Hole Navigation (Fig. 3) decreased by 50% using 3-D US vs. 2-D US guidance (p=0.046). For Bead-to-Bead Navigation (Fig. 4), normalized task completion times decreased by 77% with 3-D US guidance as compared to 2-D guidance (p=0.009). Trajectory analysis also demonstrated significant improvement in navigational accuracy using real time 3-D US as compared to 2-D US imaging. With 3-D US guidance, D_{mean} decreased from 1.62 cm to 0.87 cm (46% improvement, p=0.04) while $D_{\max}$ decreased from 3.54 cm to 1.95 cm (45% improvement, p=0.069). (For reference, D_{mean} and $D_{\max}$ with endoscope guidance were 0.30±0.04 cm and 0.92±0.18 cm, respectively.)

Biplanar image presentation improved performance by an average of 52% over 2-D US (Fig. 4) although this improvement did not prove statistically significant (p=0.16). When compared to 3-D US guidance, however, task completion times with biplanar imaging were significantly longer (p=0.009). Tool tip deviation, on the other hand, was not significantly different when comparing either 2-D vs. Biplanar or 3-D vs. Biplanar image guidance.

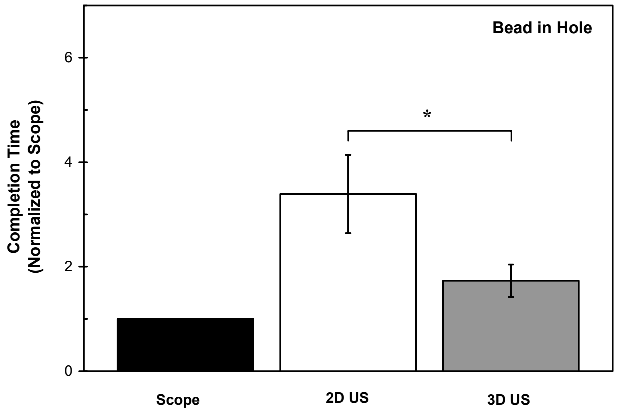


Fig. 3. Normalized task completion times for Bead-in-Hole Navigation. * p=0.046. In all figures, error bars=standard error, 2D=two dimensional, 3D=three dimensional, US=ultrasound.

Surgeon-controlled imaging (Fig. 5) did not improve task performance for 2-D US image-guided task completion (p=0.306). Similarly, there was no difference in task performance with surgeon-controlled 3-D US imaging vs. sonographer-controlled imaging (p=0.088). There was also no significant difference in D_{mean} or $D_{\max}$ for either 2-D vs. 2-D surgeon guidance or for 3-D vs. 3-D surgeon guidance.

When considering appropriate presentation of the 3-D image, changes in image perspective did not substantially decrease performance of the Bead-to-Bead Navigation task (Fig. 6). However, during completion of this task with 3-D imaging, at times, the tool shaft or the shadow of the tool obscured the target requiring a slight shift in the US

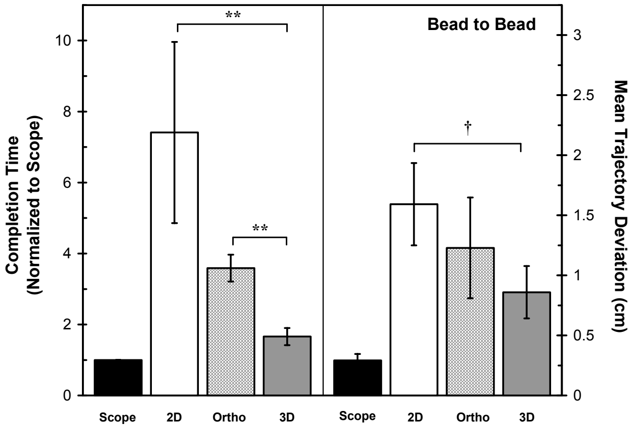


Fig. 4. Normalized task completion times and associated tool tip deviations for Bead-to-Bead Navigation. ** p=0.009, †=0.040, Ortho=biplanar 2-D imaging.

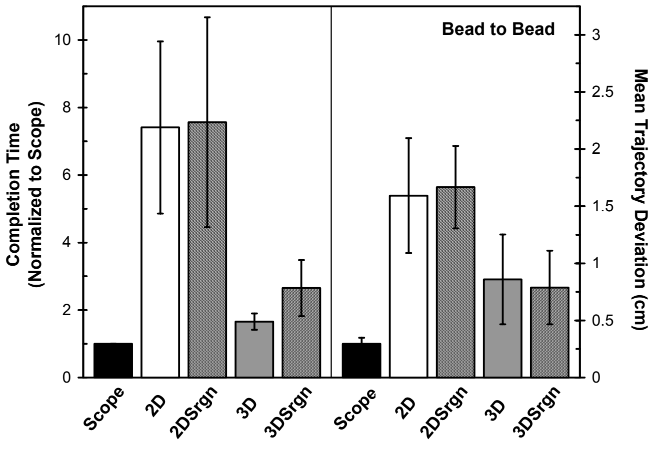


Fig. 5. Normalized task completion times and associated tool tip deviations for surgeon-controlled US during Bead-to-Bead Navigation. Task completion times and tool tip deviations were not statistically significant when comparing 2-D vs. Surgeon-controlled 2-D guidance *or* 3-D vs. Surgeon-controlled 3-D guidance (all p>0.05).

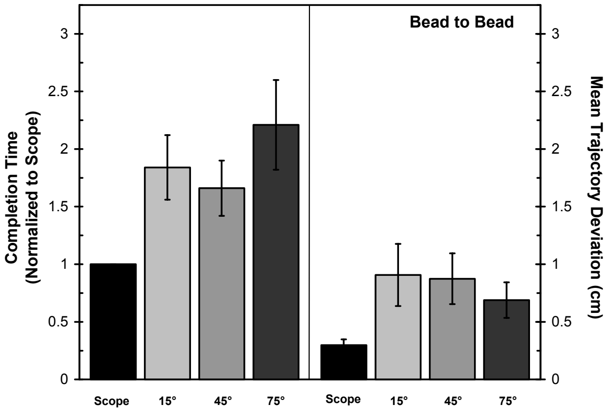


Fig. 6. Normalized task completion times and associated tool tip deviations for Bead-to-Bead Navigation with 3-D images presented at different elevations. 15° represents a horizontal projection while 45° is an isometric "natural" perspective and 75° is a more vertical perspective (all $p>0.05$).

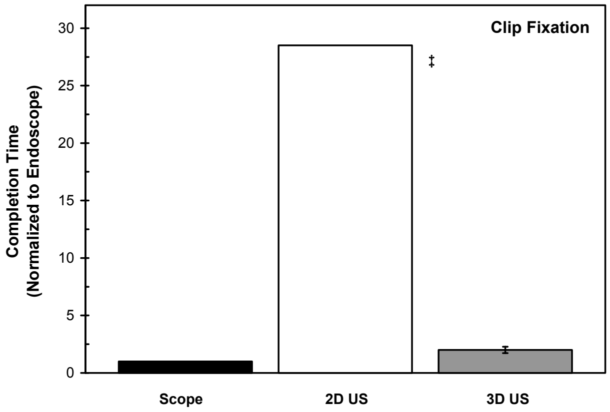


Fig. 7. Normalized completion times for clip fixation of adjacent structures using two instruments for manipulation under US guidance. ‡=Due to excessive completion times (> 240 s), evaluation of 2-D US guidance not performed by all subjects.

transducer or the instrument to relocate the exact position of the target. This line of sight interference occurred more frequently as the image perspective became either more horizontal (15°) or more vertical (75°) although the data did not reflect this at a statistically significant level. Trajectory analysis for each of these presentation angles showed only small differences in mean trajectory deviation again with no statistically significant difference among any of these different presentations.

Clip Fixation proved highly impractical using 2-D US imaging with excessive completion times (> 240 s) and error rates. However, when performed using real time 3-D US guidance, task completion times were similar to endoscope guidance times (Fig. 7) with very few misapplied clips (0.3±0.1 per attempt).

DISCUSSION

This paper examines the potential role for real time 3-D US in guiding surgical tasks with the hypothesis that additional spatial orientation information should improve performance over 2-D US guidance and may enable completion of more complex tasks using US guidance alone. Results from the validation study presented here indicate that even for basic navigational tasks, real time 3-D US can significantly improve performance over the current standard of 2-D imaging for US-guided interventions. More importantly, this study demonstrates that complex two-instrument surgical tasks (impossible with 2-D US guidance) can be performed with real time 3-D US imaging with results comparable to optical imaging. Thus, real time 3-D US may enable minimally invasive approaches to surgical diseases in locations not readily accessible by optical imaging.

The evaluation tasks in this study represent a range of difficulty from the basic navigation tasks currently guided by 2-D US in clinical practice to a much more complex task requiring the simultaneous use of two instruments which has not previously been performed under US image guidance. Both navigation and clip fixation have direct relevance for procedures which might be performed using image-guided minimally invasive surgical techniques. Examples include fetal heart valve expansion with a catheter balloon,[22] clip fixation of a repair patch to close congenital heart defects,[23] or placement of a supporting ring around a dilated valve inside a beating heart.[24] For relatively simple interventional tasks (able to be performed with one instrument), this study also shows that with 3-D US, surgeon-controlled imaging represents a safe and reliable alternative if an imaging expert is not readily available.

This study did not demonstrate any difference between task performance measures for images presented at different projection elevations. As the image pitch approaches either a horizontal or vertical extreme, some spatial orientation data is theoretically lost. Consequently, one would expect a unimodal histogram for all task performance measures with the best performance given by an isometric or "natural" image presentation. This effect was not observed in the current study possibly due to the small number of subjects (n=7). Alternatively, surgeons may be able to infer sufficient spatial orientation data from the accessory cues of shadowing and surface shading present in the 3-D image regardless of the perspective angle.[25]

Instrument shadowing and tools interposed between the US transducer and the target did at times limit user performance which could, in part, explain discrepancies between real time 3-D US and endoscopic performance. These limitations could be overcome by using several techniques including re-configuring the study tank so that the US transducer can be positioned opposite the surgical instruments to minimize shadowing (the image can then be arbitrarily rotated into a suitable orientation for the surgeon). Additional techniques for enhancing the surgeon's view of the operative field include image oscillation for improved perspective or collocation of the US image over the operative field to simulate open surgery.

Current use of 3-D US for image-guided interventions is limited due to delays from image acquisition and processing inherent in existing systems. In contrast, the real time 3-D US system evaluated in this paper has a frame rate sufficient for working inside a dynamic surgical field, and its resolution is adequate for guiding surgical instruments. Future work with dynamic, living tissues will be an important next step in assessing the clinical applicability of real time 3-D US for guiding surgical procedures. Parallel developments in image processing, surgical instrumentation, and image presentation will also enhance performance of these image-guided procedures. With these development efforts currently underway, this imaging system has the potential to improve current interventional ultrasound techniques while also enabling new minimally invasive image-guided surgical procedures.

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