Fig. 2 The target handle attached to a puncture needle

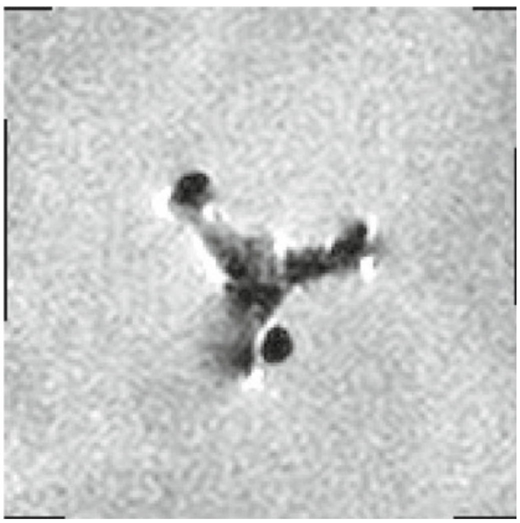

Fig. 3 The maximum artifact size of the target handle

acquisition for one image per three seconds. We found no significant loss of SNR with the use of the optical tracking system inside the MR environment. The maximum artifact size of the target handle (see Fig. 3) was 111 mm and only showed minimal difference compared to the real size of 87 mm. The ASTM test to assess magnetic attraction revealed an object deviation of less than 1° at 2.4 T/m at 35 g and is therefore below the maximum permitted deviation for MR-compatibility.

Conclusion

We hereby conclude using optical tracking for the dynamic control of the image plane of MR guided interventions is safe and feasible. The limitations of using optical tracking in the spatially limited MR-environment (see Fig. 1) are due to the necessity of line of sight [1]. Increasing the distance of the cameras and the tracking handle results in a decrease of the tracking accuracy. Since the slice thickness in MRI is typically 5-10 mm, the decreased accuracy is still sufficient for navigation in MR-guided interventions.

References

[1] Hashizume, M.; Yasunaga, T.; Tanoue, K.; Ieiri, S.; Konishi, K.; Kishi, K.; Nakamoto, H.; Ikeda, D.; Sakuma, I.; Fujie, M. New real-time MR image-guided surgical robotic system for minimally invasive precision surgery. International Journal of Computer Assisted Radiology and Surgery, Springer, 2008, 2, 317–325

[2] Moche, M.; Trampel, R.; Kahn, T. & Busse, H. Navigation concepts for MR image-guided interventions. J Magn Reson Imaging, Department of Diagnostic and Interventional Radiology, Leipzig University Hospital, Leipzig, Germany., 2008, 27, 276–291

[3] Samset, E.; Hans, A.; DiMaio, S. & Jolesz, F., A dynamic and extensible workflow-oriented software framework for image-guided therapy. International Journal of Computer Assisted Radiology and Surgery, Springer, 2007, 2, 221–229 (optical tracking most common)

[4] Seebauer, C.; Bail, H.; Wichlas, F.; Jung, T.; Papanikolaou, I.; van der Voort, I.; Rump, J.; Schilling, R.; Winkelmann, A.; Walther, T. Osteochondral Lesions of the Talus: Retrograde Drilling with High-Field-Strength MR Guidance. Radiology, Radiological Society of North America, 2009, 252, 857

[5] Tirelli, P.; De Momi, E.; Borghese, N. & Ferrigno, G. Computer Assisted Neurosurgery. International Journal of Computer Assisted Radiology and Surgery, Springer, 2009, 4, 85–91

Real-time 4D ultrasound reconstruction for improved intraoperative imaging during image-guided beating-heart interventions

D. Pace[1,2], D. Bainbridge[3], J. Moore[1], C. Wedlake[1], G. Guiraudon[1,4], D. Jones[1,4,5,6], T. Peters[1,2]

[1]Robarts Research Institute, Imaging Research Laboratories, London, Canada

[2]The University of Western Ontario, Biomedical Engineering Graduate Program, London, Canada

[3]The University of Western Ontario, Department of Anesthesia and Perioperative Medicine, London, Canada

[4]Canadian Surgical Technologies and Advanced Robotics (CSTAR), London, Canada

[5]The University of Western Ontario, Department of Physiology and Pharmacology, London, Canada

[6]The University of Western Ontario, Department of Medicine, London, Canada

Keywords Four-dimensional ultrasound · Intraoperative cardiac imaging · Image-guided therapy · Augmented reality · Minimally-invasive therapy

Purpose

Intraoperative imaging is particularly important when guiding minimally-invasive therapies performed within the dynamic environment of the beating heart. Freehand 4D ultrasound reconstruction generates a time series of 3D ultrasound volumes that represent the beating heart over the cardiac cycle and are composited from multiple 2D ultrasound images acquired during a single gated sweep of a tracked 2D transducer. This acquisition technique is flexible, allows 2D ultrasound views of target structures to be optimized to increase overall image quality, and overcomes the compromised field of view and spatial resolution of real-time 3D (RT3D) transesophageal echocardiography (TEE) and intracardiac echocardiography (ICE) [1] transducers. However, possible acquisition errors include failing to capture all structures of interest and gaps in the output volumes caused by moving the probe too quickly or patient motion. Real-time (or incremental) ultrasound reconstruction incorporates 2D ultrasound images into the 3D output volume(s) as they are acquired, allowing the output volume(s) to be updated and visualized in real-time and potentially providing sufficient feedback to prevent or correct acquisition errors. To date, however, real-time reconstruction systems have been designed exclusively for 3D imaging of stationary organs.

We have developed a real-time freehand 4D ultrasound reconstruction system for intraoperative imaging of the beating heart [2,3] that is integrated within an augmented reality environment for minimally-invasive intracardiac therapy along with a patient-specific dynamic cardiac model, tracked 2D ultrasound and virtual representations of tracked surgical tools [4]. Although applicable to a variety of interventions, including mitral valve replacement and atrial septal defect closure, this system may be especially useful during electroanatomical mapping and ablation for atrial fibrillation, particularly when generating endocardial surface models from 2D ICE [5].

Methods

Real-time 4D ultrasound reconstruction was implemented using 2D ultrasound frame-grabbing, a magnetic tracking system (Aurora®, NDI, Waterloo, Canada), retrospective ECG-gating and a discrete trilinear interpolation reconstruction kernel [2,3]. Previously assessed RMS localization errors measured 1.2-1.7 mm and 2.5-2.7 mm for 3D and 4D ultrasound reconstruction, respectively [2]. Incremental reconstruction results were visualized on three fully-interactive orthogonal slice planes (Fig. 1a), providing a detailed view of output voxels that is difficult with volume rendering. To reduce motion artifacts, 2D ultrasound images acquired when the patient's heart rate deviated considerably from a measured pre-scan baseline were not used. Using our workstation (2 dual-core Xeon CPUs, 3.2 GHz, 2 GB RAM) sixteen 240x180x240 or five 320x240x320 output volumes can be reconstructed per 4D dataset (which scales with additional memory).

A beating heart phantom (Fig. 1b) was used to confirm that providing real-time visualization confers advantages during freehand ultrasound reconstruction. The phantom consisted of a two-chambered heart within a water bath that beat 17 times per minute (bpm) while outputting a simulated ECG waveform (Shelley Medical Imaging Technologies, London, Canada). An experienced echocardiographer acquired several freehand 3D and 4D reconstructions of the stationary and beating phantom, respectively, by manually translating a transthoracic ultrasound transducer (X4 in 2D mode and SONOS 7500, Philips, Andover, USA) from above the phantom while viewing the ultrasound monitor (1) alone, mimicking an offline reconstruction system, or (2) alongside the real-time reconstruction visualization. The phantom was not shielded from direct vision to maintain reconstruction flexibility. Output volumes were reviewed following each reconstruction and, to reduce training effects, the two visualization conditions were alternated within the 3D and 4D experimental segments.

Images from two swine were obtained for a more clinically relevant evaluation. 4D ultrasound datasets (each containing two 3D volumes for this demonstration) were reconstructed using a multiplanar 2D TEE probe (M/N:T6210, Philips) whose imaging plane could be rotated at one degree increments. This effectively combines the flexibility of the freehand approach with the precision of motorized manipulation, while accommodating slight probe motions that are not considered by 3D ultrasound transducers employing internal motorized scanning. Real-time reconstruction visualization was provided via a second screen mounted above the ultrasound monitor. A tracked reference sensor sutured to the pig's back

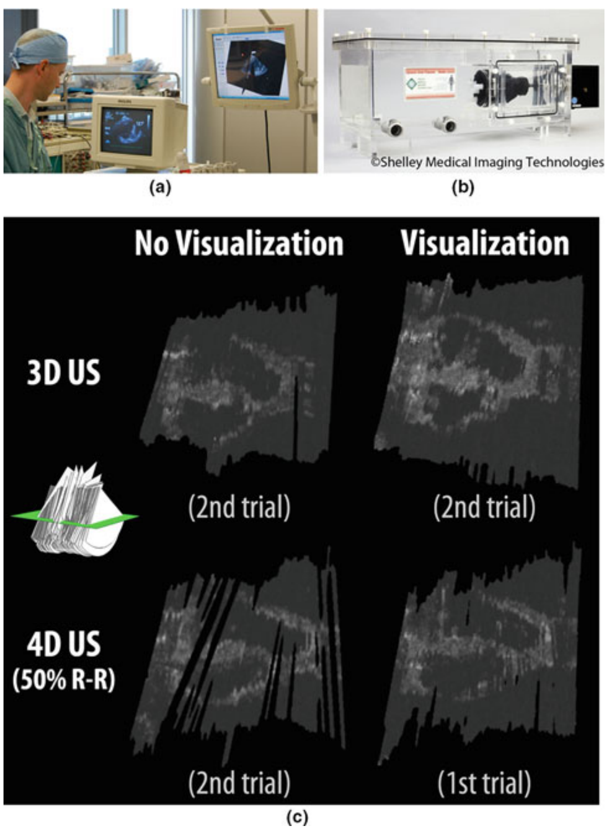

Fig. 1 (**a**) Real-time 4D ultrasound reconstruction in progress. (**b**) Beating heart phantom. (**c**) 3D/4D ultrasound reconstructions acquired with and without real-time visualization, displayed in the equivalent of a four-chamber view (input pixels = 0.40 mm^2, output voxels = 0.81 mm^3, two volumes/4D dataset)

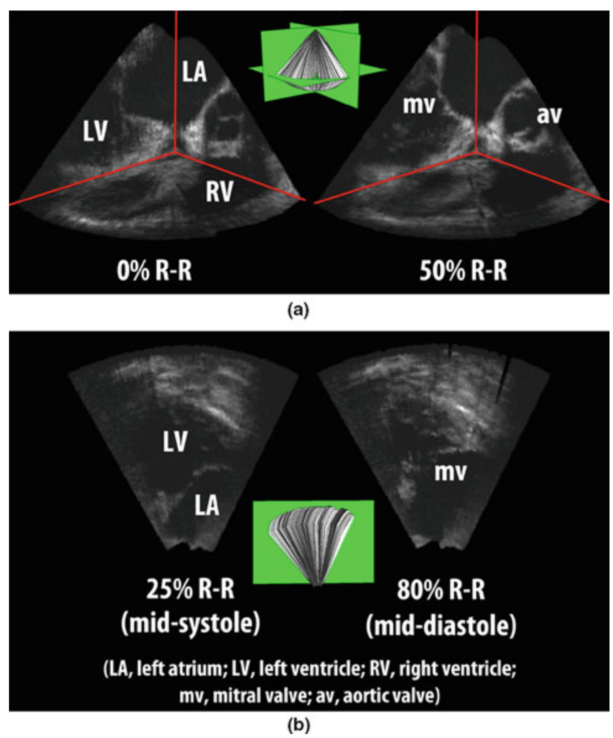

Fig. 2 Example 4D ultrasound porcine reconstructions under (a) mechanical rotational acquisition (b) manual fan acquisition (input pixels $\approx$ 0.34 mm^2, output voxels $\approx$ 0.67 mm^3, baseline heart rate $\approx$ 96–107 bpm)

compensated for any gross motion, and respiration was suspended whenever reconstructed ultrasound was acquired.

Results

Figure 1c demonstrates the benefits of real-time visualization for freehand 3D and 4D ultrasound reconstruction, particularly with respect to the number of gaps in the output volume(s). The relative simplicity of 3D ultrasound reconstruction makes the improvement slight. However, significant gaps were present in the 4D ultrasound datasets acquired without real-time visualization regardless of training, which were dramatically reduced even in the first dataset reconstructed with the aid of real-time visualization. Providing real-time visualization increased acquisition duration by factors of 2.4 (3D) and 1.8 (4D) because the requirement for slow, controlled probe motion was reinforced and gapped areas were re-acquired.

Sample porcine 4D ultrasound datasets are shown in Fig. 2. The example rotational acquisition shows all four cardiac chambers, the left atrial appendage and the mitral and aortic valves. The increased tracking error sustained during manual acquisition induced comparatively more motion artifacts in the fan output volumes, which nevertheless visualized the left atrium, left ventricle and mitral valve in this example. Given sufficient operator experience, the expected acquisition time is 3–4 minutes.

Conclusions

We have presented a real-time freehand 4D ultrasound reconstruction system for intraoperative imaging during image-guided intracardiac therapy. Unlike RT3D probes, freehand ultrasound reconstruction systems do not image natively in 3D. Nevertheless, our reconstructed 4D ultrasound datasets encapsulate the intraoperative beating heart with a wide field of view and do not require registration into the augmented reality environment's coordinate system. These qualities, along with the encouraging results from the human factors and porcine imaging studies presented here, support future investigations into their use for surgical guidance or as the basis for algorithms registering the intraoperative patient to high-quality preoperative images, ideally non-rigidly [1, 6].

References

[1] Wein W, Camus E, John M, Diallo M, Duong C, Al-Ahmad A, Fahrig R, Khamene A, Xu C (2009) Towards guidance of electrophysiological procedures with real-time 3D intracardiac echocardiography fusion to C-arm CT. Medical Image Computing and Computer Assisted Intervention (MICCAI), Lecture Notes in Computer Science 5761:9–16

[2] Pace DF, Wiles AD, Moore J, Wedlake C, Gobbi DG, Peters TM (2009) Validation of four-dimensional ultrasound for targeting in minimally-invasive beating-heart surgery. SPIE Medical Imaging 7261:15

[3] Pace DF, Gobbi DG, Wedlake C, Gumprecht J, Boisvert J, Tokuda J, Hata N, Peters TM (2009) An open-source real-time ultrasound reconstruction system for four-dimensional imaging of moving organs. Workshop on Systems and Architectures for Computer Assisted Intervention (MICCAI), http://hdl.handle.net/10380/3083

[4] Linte CA, Moore J, Wiles AD, Wedlake C, Peters TM (2008) Virtual reality-enhanced ultrasound guidance: A novel technique for intracardiac interventions. Computer Aided Surgery 13(2):82-94

[5] den Uijl DW, Tops LF, Tolosana JM, Schuijf JD, Trines SAIP, Zeppenfeld K, Bax JJ, Schalij MJ (2008) Real-time integration of intracardiac echocardiography and multislice computed tomography to guide radiofrequency catheter ablation for atrial fibrillation. Heart Rhythm 5(10):1403–1410

[6] Huang X, Ren J, Guiraudon G, Boughner D, Peters TM (2009) Rapid dynamic image registration of the beating heart for diagnosis and surgical navigation. IEEE Transactions on Medical Imaging 28(11):1802–1814

Physically-based Models for Virtual Stent Planning and Simulation Based on Open Standards

S. Scherer, T. Treichel, N. Ritter, W.-G. Drossel, O. Burgert,
Fraunhofer Institute for Machine Tools and Forming Technology IWU, Dresden, Germany

Keywords:
Endovascular Surgery · Virtual Stenting · Standardization · DICOM · OP Planning System · Finite-Element-Method

Purpose

To provide a numerical model for improved planning of stenting interventions it is initially necessary to investigate the feasibility of supporting vessel simulations and the input parameters required for that purpose. This article presents results with regard to the influencing of simulation parameters. In addition, it describes initial approaches to integrate physically-based simulation results in the clinical setting by way of medical communication standards.

Methods

For determining calculable evaluation parameters helpful for the vascular specialist, a finite element model was applied corresponding to vessel, plaque and stent. Using model variants, the influence of different material approaches and computation parameters on the simulation outcome was investigated. For the purpose of integrating computation models into a medical planning system, the necessary simulation input variables were examined for their standardisability.

Results

Model studies have shown that the computation model's closeness to reality when imaging the stent-vessel interaction largely depends on the use of a hyperelastic, anisotropic material approach for vessel description, the use of experimental data of diseased vessels as well as the consideration of plaque and individual patient's blood pressure. The efforts with respect to standardization have brought forth initial results concerning both the usability and the need for upgrading existing standards in terms of data description.

Conclusions

The simulation of stenting procedures using FEM for realistic stent-vessel interaction seems to be feasible using the described approach. A modular system architecture can serve as integration framework for the software modules involved in the process. A standardization of the interface to the FEM software is currently not achievable.

Prediction of Cardiac Motion

F. Ernst, R. Bruder, M. Pohl, A. Schlaefer, A. Schweikard
University of Lübeck, Institute for Robotics and Cognitive Systems, Lübeck, Germany

Keywords Motion prediction · Cardiac motion · Atrial fibrillation · Robotic radiosurgery

Purpose

Some movements of the human body are involuntary, like cardiac or respiratory motion. This causes problems in medical interventions which require the target structures to remain stationary. As an example, the CyberKnife is a radiosurgical device which corrects for motion of the human body by taking X-ray images and measuring respiratory motion by means of an optical tracking device. With this information, a robotic manipulator, carrying a linear accelerator, can be guided to reduce or eliminate the effects of respiratory motion.

A new application of the CyberKnife system is myocardial ablation using highly focussed radiation. To overcome system latency, the motion of the target region on the beating heart has to be forecast.

In this work, we have analysed the possibility of predicting cardiac motion using algorithms which have been shown to be successful