transmitted to the distal end of the scope, resulting in smoother insertion of the scope into the colon. Preliminary results suggest that the GII metric was successfully validated in 9 human studies to differentiate expertise in manipulating the colonoscope among novices and experts. Work is in progress to validate the metric in a larger human study.

Registration methods for gross motion correction during image-guided kidney surgery

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Keywords Image-guidance · Kidney · Registration · Minimally invasive · Conoscope

Purpose

The National Cancer Institute reported an increased incidence of kidney cancer over the past 30 years, projecting over 54,000 new cases in 2008 [1]. Surgical intervention is the established method of treatment, with partial nephrectomies preferred when physiologically practical [2, 3]. Along with nephron-sparing approaches, minimally invasive methods have gained ground due to reduced blood loss and faster recovery time compared to open resections [4]. With less invasive approaches becoming more common, the incorporation of quantitative guidance holds promise as surgeons strive toward closer margins and more spared healthy tissue.

Image guidance uses a transformation linking preoperative image-space and physical-space, requiring collection of points in both spaces. Though point-based methods are faster and more robust, non-rigid attachment of abdominal organs makes extrinsic, preoperative fiducials impractical, and intrinsic points are difficult to localize in both image and physical-space. Thus surface-based registration has proven useful in abdominal image guidance [5], despite limitations involving symmetry and local minima convergence. Such methods may have particular trouble as surgery progresses and the kidney is shifted and deformed by clamping, icing, and cutting.

To update an initial surface-based registration, a quick, reliable re-registration between perioperative and preoperative image-space would be advantageous. We previously accomplished this by extracting virtual fiducials from laser range scans (LRS) and using point-based registrations to realign image and physical-space [6]. The extension of this technique to a minimally invasive approach constitutes the next logical step. Conoscopic holography has shown promise as a minimally invasive surface acquisition method. The conoscope performs similarly to an LRS, acquiring a full point cloud for the initial surface-based registration, and later obtaining virtual fiducial locations for intraprocedural re-registration. Previous studies have shown that a conoscope can successfully be used for liver phantom registrations [7]. The current study evaluates the accuracy of conoscope-based registration in phantoms and ex vivo porcine kidneys, providing a preliminary validation of this method for minimally invasive procedures.

Methods

In our previous clinical work, perirenal fat was removed and a surgical marker was used to dot the kidney surface. LRS data were acquired then and at later stages of the procedure. The first LRS surface was registered to CT by the Iterative Closest Point (ICP) method [8], and the marker dots were extracted from all laser surfaces. These fiducials were used to register subsequent intra-operative states to the initial state.

To investigate a minimally invasive approach, the current work employed a similar procedure, using a conoscope (Optimet Optical Metrology, Ltd., Jerusalem, Israel) to acquire surface data for a phantom and ex vivo porcine kidney. Additionally, radiopaque markers were placed on these surfaces for validation of the initial surface-based registration.

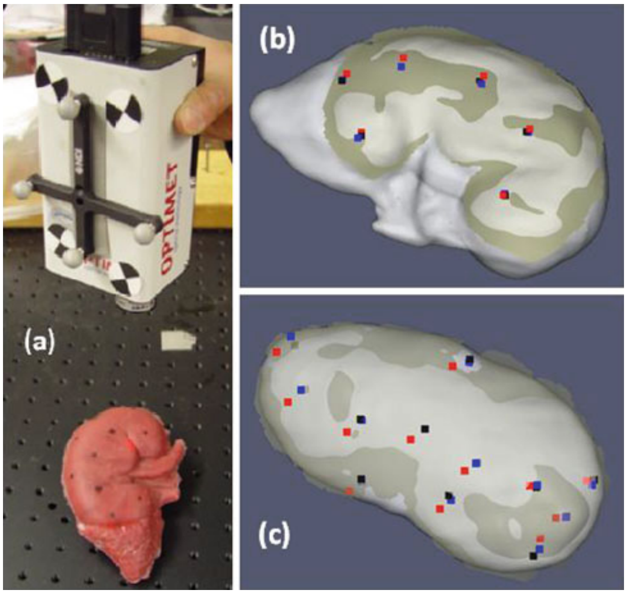

Fig. 1 **a** Conoscope and kidney phantom shown. **b** Phantom and **c** Ex vivo kidneys. CT surfaces displayed (*white*) with conoscope surface (*gold*) registered by ICP. Fiducials localized in the CT scan (*red markers*), in the initial ICP-registered conoscopic surface (*blue*), and in the conoscopic surface after point-based registration to correct for gross movement (*black*)

For the phantom, fiducial dots were marked on the kidney surface. Metal fiducials were placed over them to serve as CT-visible targets. A parallel procedure was performed using an ex vivo porcine kidney. Two kinds of radiopaque fiducials were employed: metallic washers and a barium sulfate paint. A CT scan, full conoscopic surface scan, and conoscope-localized fiducial locations were obtained for both kidneys. Each kidney was moved from its original position and slightly deformed, after which the surface fiducials were re-localized. The initial full conoscopic surface was registered to the segmented CT surface using ICP, and after movement, the kidney was re-registered via point-based methods. This methodology allows a later state to be unambiguously registered to an initial state without the need for a second full-surface scan.

Results

To unambiguously evaluate the initial surface-based registration, targets are needed. The radiopaque fiducials serve this purpose. Target registration error (TRE) [9] between the radiopaque fiducial centroids in conoscopic and CT spaces was calculated. After gross movement, conoscopic data were registered to the initial state using surface fiducials. For this registration, a leave-one-out method was employed to obtain a mean TRE between subsequent and initial conoscopic data. These registrations are shown in Fig. 1b and c.

Results indicate that alignment between the initial and subsequent conoscopic fiducials is accurate for the kidney phantom, with a TRE of 1.2 mm (Table 1). The ex vivo kidney, perhaps more easily deformed, yielded a higher TRE average of 3.0 mm. The initial surface-based registration was also more accurate for the kidney phantom, with a TRE of 2.5 mm, while the ex vivo kidney had a TRE of 4.9 mm.

Conclusion

This initial study showed that the conoscope can be used to localize fiducials and obtain a point cloud of sufficient density to drive a

Table 1 TRE for the initial ICP and subsequent point-based registrations for phantom and ex vivo kidney

	CT-to-conoscopic surface TRE (mm)			Conoscopic-to-conoscopic surface TRE (mm)[a]		
Phantom	Mean	Std	Max	Mean	Std	Max
Initial ICP	2.52	1.08	3.90	–	–	–
Subsequent point-based registration	2.33	1.05	3.67	1.22	0.52	1.79
Ex vivo kidney						
Initial ICP	4.87	1.65	6.83	–	–	–
Subsequent point-based registration	5.56	1.85	8.56	2.96	2.14	6.61

Middle column: TRE between CT and conoscopic surfaces. Right column: TRE between initial and subsequent conoscopic scans taken after gross movement

[a] Calculated by leave-one-out method

surface-based registration. Phantom results were promising, though later registrations remain dependent on the quality of the initial surface-based registration. The ex vivo kidney registration did not perform as well as the phantom. Point-based registration error in this case may be due to the ease of deformation in non-perfused, non-viable kidney tissue. The deflated state of this kidney created a flat surface over which conoscope points were acquired, and this non-descriptive surface may have adversely affected our initial registration. This work highlights the limitations in surface-based methods, namely the lack of a direct evaluation metric. Surface-based methods require the continued study of the amount and descriptiveness of the acquired surface, so that the first registration does not propagate error forward into later intra-operative states. Despite the challenges, these results support the incorporation of conoscopic data into our multi-registration workflow for minimally invasive surgical guidance in the kidney.

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Accuracy considerations in image-guided cardiac interventions: experience and lessons learned

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Keywords Minimally invasive interventions · Medical imaging and image guidance · Surgical planning · Computer-assisted surgery and therapy

Purpose

The use of medical imaging has enabled the performance of minimally invasive procedures, providing a means for visualization and guidance during interventions where direct, naked eye visual feedback could not be achieved without significant trauma: such procedures are commonly referred to as image-guided interventions (IGI) [1]. Typically, an image-guidance environment requires pre-operative images, surgical tracking, a data integration method, and a visualization and display platform (Fig. 1). While the first four processes have received extensive attention, the last process—accounting for differences between the pre-operative data and intra-operative reality—has yet to be further explored, as it leads to one of the most frequently asked questions: how accurate is the IGI system? Form a clinical perspective, the success of an intervention is assessed according to the therapeutic outcome. From an engineering perspective, navigation accuracy is constrained by the limitations of the IGS system: the overall targeting error within an IGS framework is dependent on the uncertainties associated with each of the

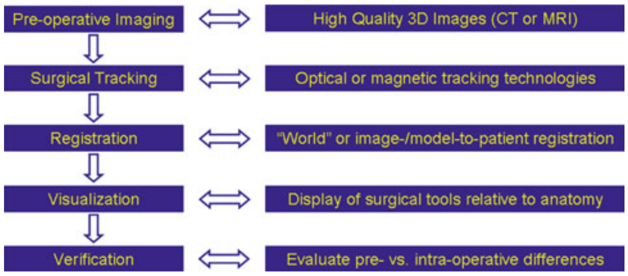

Fig. 1 Typical IGI workflow including pre-operative planning, surgical instrument tracking, patient registration, environment visualization and display, and verification of pre-operative data against the intra-operative reality