Augmented Reality Image Guidance in Minimally Invasive Prostatectomy

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Abstract. This paper presents our work aimed at providing augmented reality (AR) guidance of robot-assisted laparoscopic surgery (RALP) using the da Vinci system. There is a good clinical case for guidance due to the significant rate of complications and steep learning curve for this procedure. Patients who were due to undergo robotic prostatectomy for organ-confined prostate cancer underwent preoperative 3T MRI scans of the pelvis. These were segmented and reconstructed to form 3D images of pelvic anatomy. The reconstructed image was successfully overlaid onto screenshots of the recorded surgery post-procedure. Surgeons who perform minimally-invasive prostatectomy took part in a user-needs analysis to determine the potential benefits of an image guidance system after viewing the overlaid images. All surgeons stated that the development would be useful at key stages of the surgery and could help to improve the learning curve of the procedure and improve functional and oncological outcomes. Establishing the clinical need in this way is a vital early step in development of an AR guidance system. We have also identified relevant anatomy from preoperative MRI. Further work will be aimed at automated registration to account for tissue deformation during the procedure, using a combination of transrectal ultrasound and stereoendoscopic video.

Keywords: MRI scan prostate, image guidance, augmented reality, robot-assisted laparoscopic prostatectomy (RALP).

1 Introduction

1.1 Clinical Background

Prostate cancer, the most common cancer in men in the UK, accounted for 9157 deaths in 2008 [1]. 30201 new diagnoses of the disease were made in 2007, and the

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incidence of prostate cancer is likely to increase due to an aging population [2]. The 5 year survival rate is 71% which is aided by accurate surgical intervention and early detection using prostate-specific antigen. Radical prostatectomy is a well established treatment for organ confined prostate cancer and confers survival benefit [3].

There are three common methods for performing a radical prostatectomy. The longest-established method is open surgery, either by retropubic or perineal approach, which was first described in 1905 by H Young [4]. The description and uptake of anatomic prostatectomy in the late 1970s refined the technique of the surgery. Open surgery is still the gold standard procedure for radical prostatectomy, although it is complicated by higher rates of blood loss and a longer hospital stay than for minimally-invasive procedures [5].

Minimally invasive radical prostatectomy can be performed by laparoscopic or robot-assisted laparoscopic methods. Laparoscopic surgery increased in popularity in the late 1990s and in the hands of an experienced surgeon, can deliver good patient outcomes. However, the procedure remains technically complex and has a long and difficult learning curve due to the constraints of operating with a laparoscopic system, such as the absence of haptic feedback, a reduced range of instrument motion, and 2-dimensional visualisation during the procedure [5].

Robot-assisted laparoscopic surgery is a further advance and has been increasing in popularity in the last ten years, with estimates that over 70% of prostatectomies in the United States are now performed this way. Systems such as the da Vinci Robot have added benefits to conventional laparoscopic surgery, including 3-dimensional vision, improved ergonomics, motion-scaling and tremor loss, and an increased range of motion for surgical instruments. Despite the rapid and costly uptake of RALP, there is debate as to which modality of prostatectomy confers the most benefit to patients, as the negative outcomes of positive surgical margins, functional impairment (erectile dysfunction, urinary incontinence) due to nerve damage and iatrogenic injury to surrounding structures are equally prevalent across the surgical modalities. Proponents of robot-assisted surgery claim it is superior to open or laparoscopic techniques. However, these claims are controversial and based on low quality evidence [5,6]. It is hoped that the forthcoming LopERA trial in the United Kingdom will add high quality evidence to this debate [6].

However, of all the techniques described above, RALP has been purported to have the greatest potential for improving outcomes in the future, due to ongoing research and developments of this relatively new technology [7].

The addition of augmented reality (AR) to robotic prostatectomy will enhance and potentially standardise the accuracy of surgery. Having the cancerous growth ‘visible’ by means of AR may aid in complete macroscopic excision, particularly in the difficult region of the prostatic apex where positive cancerous margins are most common, resulting in improved oncological cure. Display of surrounding anatomy could result in improved neurovascular bundle and sphincter preservation and guide bladder neck dissection, improving the potency and urinary continence rates achievable after RALP. The real time display of adjacent organs will reduce the potential for intraoperative morbidity such as rectal injury [8].

The learning curve for robotic techniques has also been identified as a factor in surgical outcome [9]. Initial reports suggest a shorter learning curve for robot-assisted radical prostatectomy over conventional laparoscopic radical prostatectomy, with the advantage that prior laparoscopic experience may not be required [10]. However there is still a significant learning curve for robot-assisted radical prostatectomy which can be further shortened by improving the anatomical orientation within the male pelvis using AR.

We describe our research to develop image guidance technology for RALP in order to improve surgical outcomes.

1.2 Background to Augmented Reality

Image guidance is becoming an accepted tool for applications in neurosurgery, ENT, maxillofacial surgery and orthopaedics [11], where the operations are close to bone. Here there can be rigid alignment of the image to the physical space of the patient. Within the abdomen, image guidance has been proposed to aid gastrointestinal, biliary and pancreatic surgery [12].

The use of image guidance in urological surgery is as yet uncommon. There has been one report of an AR guided adrenalectomy and one of image guided partial nephrectomy [13,14]. Both these studies used preoperative CT scans to define anatomy intraoperatively.

Transrectal ultrasound real-time guidance has been utilised in both open and laparoscopic radical prostatectomy. The authors suggested that this modality was helpful in identification of prostate margins and neurovascular bundles during surgery [15]. However, this technology has not become widely used, which may be due to the technical challenges of intraoperative ultrasonography, the need to have a ultrasonographer present throughout the procedure and the lack of high quality evidence showing improvements in patient outcome.

As yet, no studies have utilised preoperative MRI scans in this anatomical region for image-guided surgery. MRI is the imaging modality of choice in prostate cancer, as it enables clear identification of intraprostatic anatomy and margins. These are both poorly defined on CT [16]. The use of MRI may also enable clear delineation of the neurovascular bundles running adjacent to the prostate. Damage to these structures during a prostatectomy is thought to be responsible for the functional problems that are reported after surgery.

Combining intraoperative transrectal ultrasound scans with preoperative MRI may enable real-time image overlay during prostatectomy. However, transrectal probes may alter the shape of the prostate, which could have implications during both image reconstruction and overlay.

This project aims to bring AR image guidance to radical prostatectomy by utilising preoperative MRI imaging. AR surgical guidance has the potential to reduce morbidity and improve outcome for prostate cancer patients. This project will build such a system and begin to evaluate its clinical efficacy for prostatectomy.

2 Methods

2.1 MRI Scanning, Segmentation and Image Overlay

Ten patients with histologically proven early stage prostate cancer were listed for robotic prostatectomy at St Mary's Hospital, Imperial College Healthcare NHS Trust, London. This cohort all underwent conventional 3T CUBE MRI scans of the pelvis preoperatively. Three patients also underwent pre-biopsy endoanal 3T CUBE MRI scans to determine the effects on prostate deformation and enable comparison with conventional scans. None of these patients has proceeded to prostatectomy as yet, therefore these scans have not undergone segmentation and overlay.

An anatomical protocol was established to guide the segmentation. The following structures were deemed important to identify as a minimum requirement: prostate, bladder, urethra, vas deferens, seminal vesicles, rectum, neurovascular bundles and ureters. Other structures were identified as deemed necessary at the time of segmentation. The scans underwent manual segmentation and reconstruction by a specialist MRI consultant radiologist to form a 3 dimensional reconstruction.

Intraoperative recording of the robotic prostatectomies took place via a stereo-recording system connected to the standard equipment stack in theatre. All patients were consented pre-MRI and pre-surgery for their images to be used for the purposes of this study.

Post-operatively, the 3-dimensional reconstructed view was aligned to the console view for the purpose of retrospective evaluation by the surgeon.

2.2 Establishing the Need for an Image Guidance System

The theoretical benefits of image guidance have been discussed above. However, there is no qualitative data in the literature to support its development or to gain further insight into the uses, benefits and applicability of a system. A user-needs analysis was therefore performed. This was undertaken by means of semi-structured interviews on surgeons who perform minimally-invasive prostatectomy (figure 1). The stages of minimally invasive prostatectomy have been described elsewhere [17]; this structure was used to make the interview systematic. The interviews were transcribed in real-time and then underwent qualitative analysis to determine the perceived technical difficulties of the current procedure and the future benefits of an image guidance system.

2.2.1 MRI Scanning Modality

Fig. 2(a) shows a conventional 3T scan, clearly showing the anatomical boundaries of the prostate and surrounding anatomy. By contrast, Fig. 2(b) shows an MRI scan taken using an endoanal coil. Comparison of these images reveals subtle differences. The endoanal MRI image shows deformation of the prostate due to the ano-rectal probe, and more defined intraprostatic anatomy. As well as providing better contrast in this region the use of the endoanal coil may closer mimic the tissue deformation due to intraoperative transrectal ultrasound should this become our method of soft tissue tracking.

Augmented Reality Guidance for Robotic Prostatectomy
What do Surgeons want from a system?

1. What type of minimally-invasive prostatectomy do you perform?
2. How many have you performed?
3. Do you follow the 9 stage system previously described?
4. Do you think an image guidance system would be helpful, and if so, how?
5. What complications could an image guidance system help to avoid?
6. Are there any other steps in the procedure where use of image guidance might be helpful?
7. What are the requirements for successful implementation from a surgical point of view?

	What are the technical challenges at each stage?	What structures/anatomy would be useful to identify at each stage? How might an image guidance system help?
1. Incision of peritoneum		
2. Incision of endopelvic fascia		
3. Ligation of dorsal vein complex		
4. Dissection of the bladder neck		
5. Seminal vesicle dissection		
6. Denonvilliers posterior dissection		
7. Nerve-sparing right and left		
8. Mobilising apex		
9. Anastamosis		

Fig. 1. Semi-structured interviews for urological surgeons

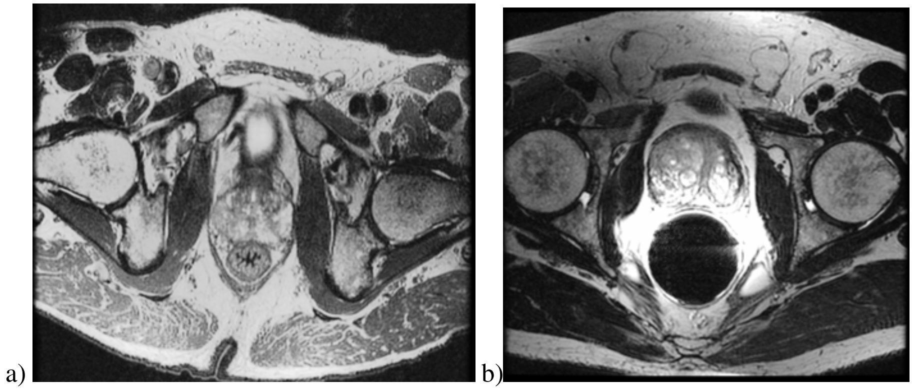


Fig. 2. Example MRI scans - conventional (a) and with an endoanal coil (b)

2.2.2 MRI Segmentation and Image Overlay

MRI scans were successfully segmented and reconstructed in 3D. Relevant anatomy was identified and coloured. The images were then calibrated and overlaid onto still images of a recorded robotic prostatectomy.

The combined images show the anatomy of the pelvis from the viewpoint of the operating surgeon. The images are scaled to reflect the magnification seen intraoperatively.

Fig. 3 shows the appearance of the pelvic cavity at the beginning of the procedure. There is a significant pneumoperitoneum moving the abdominal wall anteriorly and therefore increasing the space for the robotic instruments to work. In Fig. 3(b) the overlay demonstrates segmented and reconstructed pelvic organs from the preoperative MRI scan that have been overlaid onto the operative image. The prostate (green), seminal vesicles (pink) and left sided neurovascular bundle (yellow) can be seen along with the pelvic bony structure (white/grey). The bladder has been removed

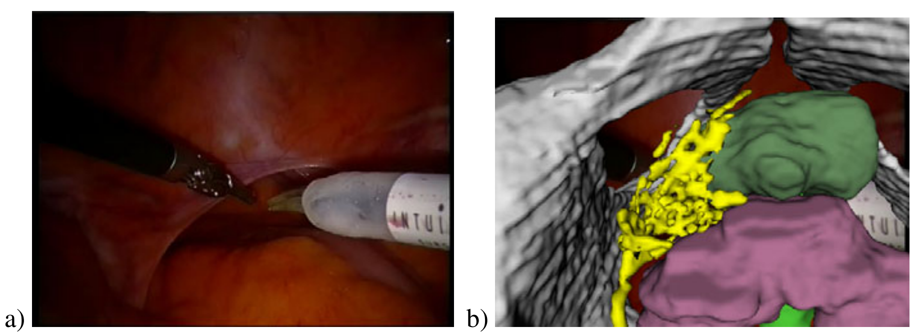
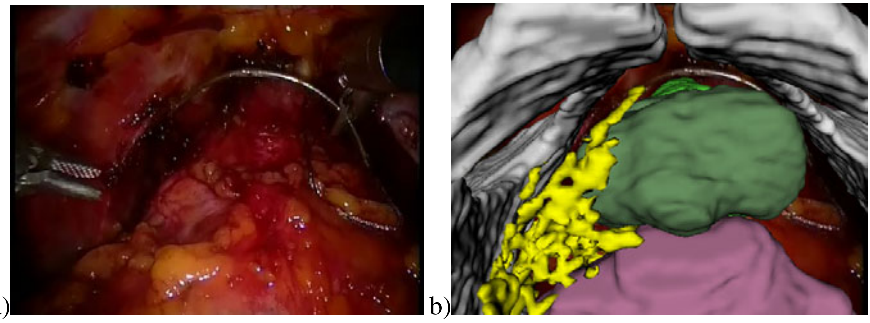


Fig. 3. The pelvic cavity at the beginning of the procedure – the operative view (a) and the same view with overlay (b)



a) b)

Fig. 4. Dorsal vein complex without (a) and with (b) overlay

from the image as it was full during the preoperative MRI and occludes the other structures when overlaid. Furthermore, during the procedure the patient has a urinary catheter and therefore the bladder is decompressed. Note that these images do not reflect the pneumoperitoneum and therefore the structures are not completely aligned.

Fig. 4 shows the dorsal vein complex about to be ligated by the surgeon. The needle is clearly visible in the screenshot. Again, the pneumoperitoneum makes accurate overlay difficult other than for the bony pelvis. Interestingly, the neurovascular bundle is not clearly visible on the screenshot, but is obvious on the augmented reality overlay.

2.3 Establishing the Requirements and Use of an Image-Guided System

Initial results of the questionnaire were encouraging. All surgeons believed that the system would be useful, although none believed that the system was of any benefit for stages 1, 2 and 9. All surgeons felt that the system would be of particular benefit to novice robotic surgeons and could help to accelerate the learning curve.

In stage 3, visualisation of the depth of the dorsal venous complex and position of the urethra was felt to be a potentially useful addition to aid needle placement and avoid urethral injury. Most surgeons felt that image guidance in stage 4 could help to preserve the bladder neck if required, and also prevent inadvertent entry into a large middle prostatic lobe. Seminal vesicle dissection was felt to be a technically challenging procedure (stage 5), although image guidance was not universally felt to be of help, other than initial location of the vesicles. One surgeon noted that neurovascular bundles did run close to seminal vesicles, and visualisation of these prior to dissection could help avoid iatrogenic injury. All surgeons agreed that stage 6, which commences with a dissection of Denonvillers fascia, could be made safer by visualising the rectum posterior to the fascia and guiding the depth of dissection. Rectal injury is a concern during this part of the procedure.

The development of an image guidance system was felt to be of greatest benefit in stages 7 and 8. High precision surgery in these areas can result in improved functional and oncological outcomes, by preservation of the neurovascular bundles and complete excision of a cancer. Stage 7 begins with the division of the lateral pedicles. Surgeons felt that identification of the neurovascular bundle in relation to the lateral pedicle would be a very useful development, and would aid nerve-sparing. One surgeon commented that anatomical differences between patients at this stage of the surgery made nerve-sparing a potentially difficult procedure, and one that image guidance could make much safer. Stage 8 involves complete dissection of the prostate down to the apex. Image guidance was felt to be useful here on two grounds. Firstly, the image guidance could show the cancerous tumour within the prostate and therefore guide complete excision during surgery, making a positive cancer margin less likely. Secondly, there was concern that surgeons at present may injure the external sphincter during the apical dissection, which image guidance could help to avoid.

More generally, surgeons stated that operative complications that could be avoided were any iatrogenic injury and inadvertent incision of the prostate. One surgeon commented that the system must work in real time when developed, in order to avoid lengthening the surgery.

3 Discussion and Future Work

We have demonstrated the capability of using preoperative MRI images to form a 3 dimensional anatomical model. Furthermore, we have enabled successful overlay and alignment of the reconstructed MRI image onto the stereo view that the surgeon would see during a robotic prostatectomy, thus giving graphical representation of intraoperative anatomy. We have identified which anatomical structures are useful to identify at certain key stages of the surgery. This is a vital stage in establishing the clinical need for image guidance in RALP.

There are a number of technical developments in progress. We are researching methods to provide a smooth and automated segmentation of the 3D MRI scan. Clearly the soft tissue deformation due to pneumoperitoneum and surgical mobilisation currently results in suboptimal registration. This challenge needs to be overcome to enable accurate image guidance intraoperatively. A registration technique that does not take account of the surgery-induced anatomical deformities will be of little use in improving surgical accuracy. In particular, preservation of the neurovascular bundles (aiding urinary continence and erectile function) and accurate mobilisation of the prostatic apex (aiding complete oncological resection) require high surgical precision, which can only be promoted by an accurate, deformable, image guidance system.

We are researching possible methods of maintaining alignment in the presence of soft tissue deformation using transrectal ultrasound to follow the motion of the prostate and nearby structures. We have anticipated that transrectal intraoperative ultrasound would significantly alter the shape of the prostate due to direct pressure. For this reason we are investigating whether the MRI should be performed with an endo-anal coil (rather than a pelvic coil) in order that the soft tissue deformation is similar to that when the transrectal ultrasound probe is inserted. We are performing further research into the use of the steroendocsopic video to reconstruct the viewed surface for intraoperative registration. For accurate live-overlay to take place the problem of soft tissue motion needs to be addressed.

It is expected that the overall system will lead to two major improvements in practice. Firstly, we expect both oncological and functional outcome improvements in patients who undergo robotic prostatectomy for early-stage prostate cancer as a result of image guidance. Secondly, we anticipate that the learning curve of the procedure will be improved for novice surgeons. Both of these developments would be of significant benefit to prostate cancer patients.

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