6

Navigated Ultrasound in Laparoscopic Surgery

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1. Introduction

Open surgery is the gold standard for abdominal surgeries. But over the last few decades, there has been an increasing demand to shift from open surgery to a minimally invasive approach to make the intervention and the post-operative phase less traumatizing for the patient. Advantages of laparoscopic surgery include decreased morbidity, reduced costs for society (less hospital time and quicker recovery), and also improved long-term outcomes when compared to open surgery. During laparoscopy, the surgeons make use of a video camera for instrument guidance. However, the video laparoscope can only provide two-dimensional (2D) surface visualization of the abdominal cavity. Laparoscopic ultrasound (LUS) provides information beyond the surface of the organs, and was therefore introduced by Yamakawa and coworkers in 1958 (Yamakawa et al., 1958). In 1991, Jakimowicz and Reuers introduced LUS scanning for examination of the biliary tree during laparoscopic cholecystectomy (Jakimowicz & Ruers, 1991). It seemed that LUS gave valuable information and has since expanded in use with the increase in laparoscopic procedures. LUS is today applied in laparoscopy in numerous ways for screening, diagnostics and therapeutic purposes (Jakimowicz, 2006; Richardson et al., 2010). Some examples of use are screening, like stone detection or identification of lymph nodes, diagnostic, like staging of disease or assessment of operability and resection range, and therauptic, like resection guidance or guidance of radio frequency and cryoablation. Harms and coworkers were the first to integrate an electromagnetic (EM) tracking sensor into the tip of a conventional laparoscopic ultrasound probe (Harms et al., 2001) and this made it possible to combine LUS with navigation technology, solving some of the orientation problems experienced when using laparoscopic ultrasound. The combination of navigation technology and LUS is becoming an active field of research to further improve the safety, accuracy, and outcome of laparoscopic surgery.

Navigation is the combined use of tracking and imaging technology to provide a visualization of the position of the tip of a surgical instrument relative to a target and surrounding anatomy. Various display and visualizations methods of both instruments and the medical images can be used. Preoperative images are useful for planning as well as for guidance during the initial phase of the procedure as long as the target area is in the retroperitoneum (Mårvik et al., 2004). When preoperative images are registrated to the patient, the surgeon is able to use navigation to plan the surgical pathway from the tip of the instrument to the target site inside the patient. Thus, navigation provides the intuitive correspondence between the patient (physical space), the images (image space that represent the patient) and the tracked surgical instruments. However, when the surgical procedure starts, tissue will change and preoperative data will no longer represent the true patient anatomy. LUS then makes is possible to update the map for guidance and acquire image data that display the true patient anatomy during surgery. Preoperative CT images will, however, still be useful for reference and overview as illustrated in figure 1, showing various display possibilities using LUS and navigation in laparoscopy. An example of simple overlay of tracked surgical tools onto a three-dimensional (3D) volume rendering of computerized tomography (CT) images is shown in figure 1A. In this figure, we used the preoperative 3D CT images for initial in-the-OR planning of the procedure. The view direction of the volume was set by the view direction of the laparoscope. The LUS image could be displayed in the same scene, with an indication of the probe position in yellow. Furthermore, when 3D preoperative images are displayed together with 3D LUS, anatomic shifts can easily be visualized and measured, thereby providing updated information of the true patient anatomy to the surgical team as illustrated in figure 1C. This may improve the accuracy and precision of the procedure. Additionally, the tracked position of the LUS probe can be used to display the corresponding slice from a preoperative CT volume, providing improved overview of the position of the LUS image as shown in figure 1D. Having 3D LUS vailable, it is possible to display these data the same way as traditional orthogonal display of MR and CT volumes, as shown in figure 1E-G. Intraoperative augmented reality visualizations in combination with navigation technology could be valuable for the surgeons (Langø et al., 2008). A possible future development, useful for spotting the true position of lesion and vessels and hence detect anatomic shifts quickly, would be to introduce LUS data into such a multimodal display.

The overall goal of all medical technology mentioned in this chapter is to improve the safety and clinical outcome for the patients. In addition, by introducing technology, it is an aim that the minimal access approach can be feasible for more procedures. Guidance solutions must therefore be designed to improve the work for surgeons and enabling younger/less experienced surgeons to perform surgical procedures with better quality and precision and with increased safety for the patients than achieved without using the technology. We believe that LUS and navigation technology in laparoscopy procedures are such technologies. However, although surgeons believe that LUS has advantages, only 43 % of the respondents in a survey claimed to use it routinely (Våpenstad et al., 2010). The surveyed surgeons were largely positive towards an increased use of LUS in a 5 years perspective and believed that LUS combined with navigation technology would contribute to improving surgical precision of tumor resection.

We present the main technological components involved in navigated ultrasound in laparoscopy. In addition, we provide an overview of ongoing technological research and development related to LUS combined with navigation technology. This chapter could serve as: 1) an introduction for those new to the field of navigated LUS; 2) an overview for those working in the field and; 3) as a reference for those searching for literature on technological developments related to navigation in ultrasound guided laparoscopic surgery.

PubMed[1], Google Scholar[2], and the IEEE database[3] were searched to identify relevant publications from the last ten years. Additional publications were identified by manual

[1] www.ncbi.nlm.nih.gov/pubmed/

search through the references from the key papers found. In this chapter we focus on publications published in the last five years. The search was limited to navigated LUS including variations such as ultrasonography, sonography, and echography, in combination with key words such as navigation, tracking, endoscopy, and 3D ultrasound. Publications covering only 3D ultrasound acquisition (e.g. volume estimations and visualization) were not included. Furthermore, we excluded papers on percutaneous techniques, open surgery approach, transrectal ultrasound guided laparoscopic prostatectomy, and transcutaneous guided radiofrequency ablation procedures. Furthermore, when groups have published same studies in both scientific papers and conference presentations, we only included data from the full peer reviewed paper in the overview.

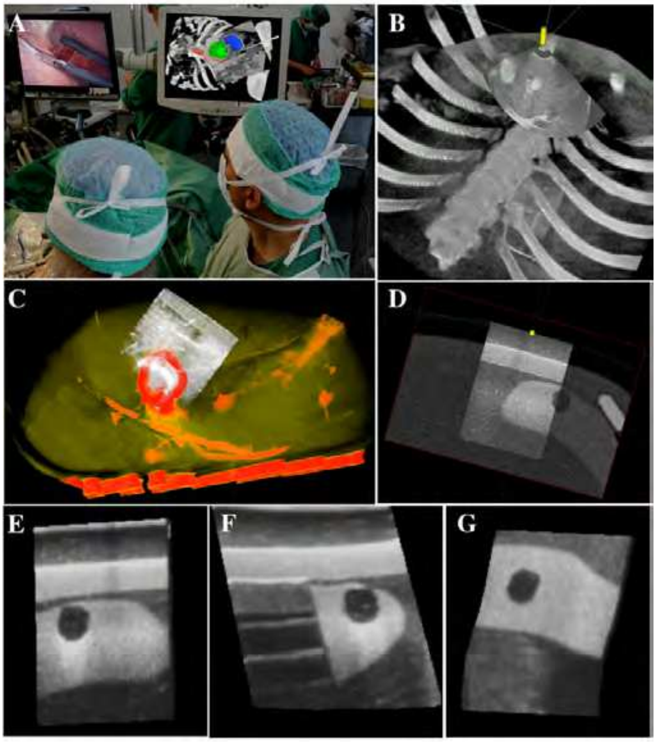

Fig. 1. Illustration of visualization methods for navigation in laparoscopy. A) Navigation during adrenalectomy using preoperative CT (3D and 2D). B) Live animal model (pig) experiment showing navigated LUS combined with preoperative images (CT volume rendering). This solves the orientation problems and improves overview . C) Multimodal display of 3D LUS (volume rendering) and 3D CT from an *ex vivo* experiment showing that the tumor position has changed. D) Anyplane slicing from CT controlled by the LUS probe and overlaying the LUS onto the corresponding CT slice (phantom). E-G) Orthogonal slices from a 3D LUS scan (phantom).

[2] scholar.google.com
[3] ieeexplore.ieee.org

2. Navigated ultrasound in laparoscopic surgery

We introduce all the relevant technologies related to navigated LUS and present a literature overview.

2.1 LUS probes

Intraoperative ultrasound systems are inexpensive, compact, mobile, and have no requirements for special facilities in the operating room (OR) compared to MRI or CT. Ultrasound image quality is continuously improving and for certain cases (e.g. liver) LUS could obtain image quality comparable to what is achieved in neurosurgery, as the probe is placed directly on the surface of the organ. In neurosurgery, the image quality of ultrasound has been demonstrated previously by our group (Unsgaard et al., 2002). The most common LUS probe is a flexible 2- or 4-way array, linear or curved, with a frequency range of 5-10 MHz. Typical imaging depths are in the range 0-10 cm, but with 5MHz deeper imaging can be performed. The LUS transducers usually have a footprint of less than 10 mm wide to fit through trocars and 20-50 mm long. They can be manipulated at the shaft allowing real time images at user-controlled orientations and positions, depending only on the specific probe configuration. Figure 2 shows various configurations of LUS probes, while Table 1 provides an overview of currently available probes.

Most LUS probes can be sterilized (Rutala, 1996) either with Sterrad, ethylene oxide, 2% glutaraldehyde, or Cidex OPA (Benzenedicarboxaldehyde, Ethicon Inc., USA). As an alternative, they can be put into sterile sheaths. Some probes also support low-temperature hydrogen peroxide gas plasma sterilization techniques. Gas plasma sterilization is shorter, and aeration and ventilation of the probe after sterilization is not necessary.

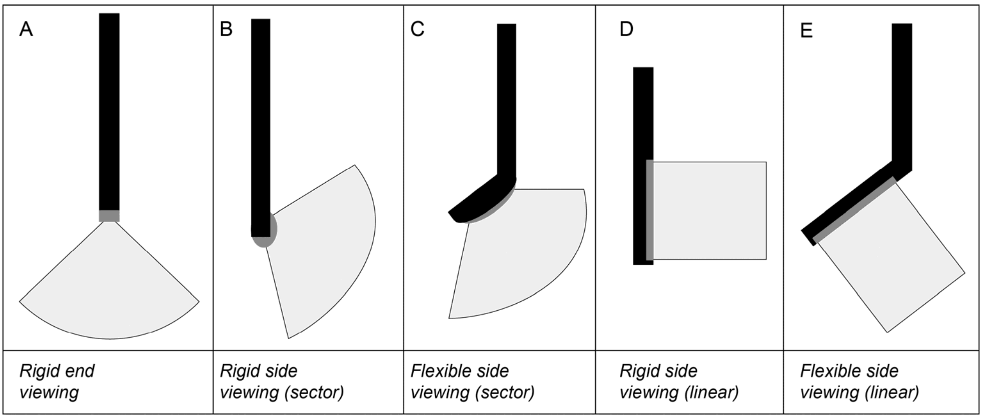

Fig. 2. Configurations of different LUS probes (Solberg et al., 2009). Option B can also be forward viewing like the Toshiba probe in Table 1.

Vendor	Probe	Frequency	Type of probe (see Fig. 2)	Transducer length, scan angle, other
Aloka	UST-52109	3-7.5 MHz	A	10 mm, 90°
	UST-5524-LAP	4-10 MHz	E	38 mm
	UST-5526L-7.5	5-10 MHz	D	33 mm
	UST-5536-7.5	5-10 MHz	E	38 mm
BK Medical	8666-RF	5-10 MHz	E	30 mm, Puncture and biopsy guide
Hitachi	EUP OL531	5-10 MHz	C	120°, Biopsy and therapy
Toshiba	PEF 704LA	5, 7.5, 10 MHz	E	34 mm
	PVM 787LA	5, 7.5, 10 MHz	B	85°
Gore	Tetrad VersaPlane	7.5 MHz (center frequency)	E	56 mm
Philips / ATL	LAP L9-5	5-9 MHz	E	NA
Esaote	LP323	4-13 MHz	E	NA

Table 1. LUS probe models from various manufacturers. Relevant specifications are also given.

2.2 Limitations with 2D LUS technology

Challenges with conventional (2D) LUS include the limited field of view compared to CT or MRI, and that LUS is dependent on the surgeons' experience and competence level in both performing the examination and interpreting the images. A limited field of view contributes to interpretation difficulties, especially for surgeons not experienced with ultrasound. An important factor is the difficulty in interpreting the orientation of the LUS image in relation to other images such as the video laparoscope and preoperative images.

Ultrasound, compared to CT and MRI, usually has a lower signal-to-noise ratio, and the specular nature of ultrasound images may cause shadowing, multiple reflection artifacts, and variable contrast. The introduction of ultrasound contrast agents and new processing techniques like ultrasound based elastography processing (strain) could provide new possibilities due to further improved image quality and structure detection.

The LUS probe is inserted through a trocar and the transducer shaft can only be manipulated along that pivot point where the proximal shaft is fixed at the insertion port. When the probe is pivoted the plane of view is changed and this can cause disorientation. Thus, constant reference to the orientation of the probe on the laparoscopic image and/or some other reference are necessary. The limited access to the organs from different angles due to trocar placement often makes it difficult to obtain a complete overview of the organ using conventional 2D LUS. One of the limitations with 2D LUS is difficulty in maintaining a view of the distal part of an instrument. This problem could be solved by real time 3D LUS (next section) or navigation combined with 2D LUS as will be presented later.

2.3 3D LUS

Real-time monitoring of the position of surgical instruments in relation to the patient's current anatomy is necessary for accurate image guided therapy. This could be achieved using 3D LUS. There are different methods to obtain 3D LUS. One method would be to make use of 3D LUS probes, which are not yet available commercially. But papers about development of such probes have been published (Light et al., 2005). 3D LUS can also be obtained by freehand scanning over the area of interest and tracking the LUS image as mentioned previously. The 3D reconstruction process may be implemented in many different ways (Solberg et al., 2007), depending on speed and quality requirements. 3D LUS imaging provides the possibility to slice the volume in any direction (figure 1E-G), providing otherwise physically unobtainable 2D slices. Tracking the LUS probe enables navigation, presented next.

2.4 Navigation

Navigation combines imaging and tracking technology thus enabling steering of surgical tools into the body based on image information and minimal access. Using navigation it is possible to perform visualization of multiple images from different sources as well as instruments in a common scene. To achieve surgical navigation based on preoperative images it is necessary to perform a registration, calibration and tracking. The following sections discuss these procedures.

2.4.1 Registration

Registration is the process of relating images to each other or relating the images to the patient. Using only intraoperative images like ultrasound for navigation purposes, no registration is necessary as the images are acquired within the tracking/patient coordinate system itself (Figure 3). Using preoperative images, registration of the preoperative images to the patient (reference frame attached to the OR table) is required to perform navigated surgery. Such registration is conventionally performed using fiducial markers or anatomical landmarks. The points are marked in both the images and on the patient using a navigation pointer (Figure 3). The registration accuracy, showing the calculated match between preoperative images and the patient is usually provided to the user after the point match is calculated. The error value provides an indication of error when using the preoperative images for guidance. However, this error will increase during surgery due to shifting anatomy. The use of multimodal image display, real time imaging (LUS) in combination with preoperative data, can potentially help detect and correct for possible anatomic shifts. For laparoscopic navigation, LUS vessel data may be used for CT-to-LUS vessel based registration to update the preoperative data for a better fit the patient data (Reinertsen et al., 2007). The reader is referred to the review paper by Maintz and coworkers (Maintz & Viergever, 1998) for further details on registration techniques.

2.4.2 LUS probe calibration

To perform a freehand 3D LUS scan or perform navigated LUS, a calibration procedure must be performed. This procedure determines the location of the LUS image in space in relation to the tracking sensor attached to the LUS probe (Mercier et al., 2005) as shown in

Figure 3. The procedure is crucial for reconstructing an accurate and geometrically correct LUS volume. A precise calibration can be best obtained by scanning a phantom with a known geometry. The features are identified in the ultrasound image of the phantom and these features are also located in physical space. The spatial relationship between the two data sets is computed in the calibration process. Some of the commonly used phantoms for probe calibration are (Mercier et al., 2005):

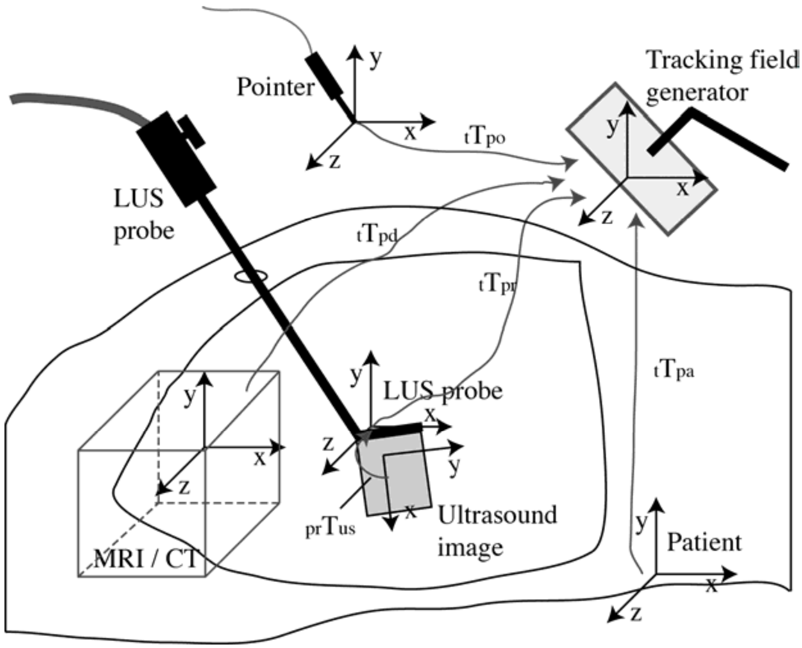

Fig. 3. The various coordinate systems involved to achieve navigated LUS in combination with preoperative data. The transformation matrices (T) shows how the various coordinate systems are linked to the tracking field generator system (arrows). ${}_{t}T_{po}$ is pointer position relative to the tracker, ${}_{t}T_{pd}$ is the preoperative data position after registration to the patient, ${}_{t}T_{pr}$ is the LUS probe position, ${}_{pr}T_{us}$ is the ultrasound image position relative to the LUS probe sensor (the probe calibration procedure establishes this transformation), and ${}_{t}T_{pa}$ is the patient reference sensor position.

- *Single point target and cross wire phantoms*
- *Multiple point targets and cross wire phantoms*
- *2-D shape alignment phantoms*
- *Wall phantoms*

It is possible to bring all the objects in the operating room into a common coordinate system by attaching position sensors to all surgical instruments, including the LUS probe (Figure 3), and a reference position sensor to the patient. However, both registration of preoperative images to the patient and probe calibration affect the overall accuracy of a navigation system (Lindseth et al., 2002; Lindseth et al., 2003). So the registration and calibration procedures must be selected carefully to reduce the error introduced in the navigation system to aid effective and accurate laparoscopic procedures. For a detailed descriptions about the various calibration methods, the reader is referred to Mercier *et al* (Mercier et al., 2005).

2.4.3 Tracking of surgical tools

There are four common technologies for tracking medical instruments: electromagnetic (EM), optical, mechanical arm and acoustic (Cinquin et al., 1995). EM or optical are most commonly used technologies for tracking in medical applications. Optical systems have a high accuracy, but require a free line of sight between the sensors/markers and the cameras. Optical methods are limited to rigid instruments. In laparoscopic surgery, independency from line of sight is important in order to facilitate the tracking of flexible instruments (including LUS probes) inside the human body. For this reason, EM tracking systems are most suitable as they are unaffected by sensor occlusion. However, distortions may occur from metallic objects in the working space that induce perturbations of the EM field. This will be discussed in detail later.

2.4.4 Visualization and display

In general, 3D volumes have a number of display and visualization possibilities that are not dependent upon using navigation technology. Using navigation technology it is, however, possible to steer the display using surgical tools or pointers. In addition, navigation and tracking technology is necessary to track positions of 2D ultrasound probes in order to reconstruct the images into a 3D volume, that can be displayed in various ways. Most medical images relevant in laparoscopy may be displayed either in 2D or 3D (pseudo-3D or true stereoscopic 3D), regardless of the image source being 2D or 3D. In addition, data from several sources/modalities may be displayed together as mentioned. To allow easier presentation of multimodal images, a common method is to extract interesting areas and present these as differently coloured surface models (segmentation).

3D display examples of multimodal images are:

- Rendering of surface models from multiple data sources.
- Volume rendering of one data source, with surface models from other data sources (Figure 1A).
- Volume rendering of multiple data sources (Figure 1C). This usually requires different colouring to distinguish the volumes from each other. Surface models may also be included.

2D display examples of multimodal images:

- One data source in each 2D display. For 3D data sources, each data source may have several 2D displays showing slices in different directions, e.g. axial, coronal and sagittal, as shown in Figure 1E-G.
- Several data sources are shown in each 2D display, the smaller or more detailed sources obscuring others.
- Several data sources in each 2D display using blending with see-through effects (the use of colours is useful).

The physical positions of the data shown in the different 2D views may be linked, and the same position in all views may be marked with a crosshairs or similar. 3D and 2D may also be combined in one 3D display by showing the 2D with correct placement in 3D. Several different 3D volume rendering methods with different rendering speed and quality may be used (Karadayi et al., 2009). Different transfer functions and filters may also improve the volume visualization quality. Fast, relatively high quality volume rendering is available today with graphics processing units (GPUs).

Even with these visualization methods available, the orientation problem in laparoscopy is even more challenging compared to other surgical disciplines. The reason is that the video laparoscope shows an image from a different angle than the LUS probe, neither of them necessarily viewing the patient anatomy at the same angle as the surgeon. Using navigation technology makes it possible to display the LUS data from various directions independently of the ultrasound acquisition direction, which may be important for interpretation of essential structures and lesions (Solberg et al., 2009).

2.5 Literature overview on navigated LUS

Only very few review or overview papers were found that partly covers the topic of navigated LUS, and none of them represent a complete overview on the area. The few relevant reviews were the following:

i. Navigation and computer assisted systems for endoscopic soft tissue surgery (Baumhauer et al., 2008). The paper informs the reader about new trends and technologies in the area of computer-assisted surgery for soft tissues in general. It contains a few references to papers dealing with navigated LUS.
ii. Navigation and image-guided hepatobiliary-pancreatic surgery (Lamadé et al., 2002).
iii. Interventional navigation systems for treatment of unresectable liver tumor (Phee & Yang, 2010). The authors only report one publication on LUS based navigation.

Below we present an overview of findings in the literature, limited to LUS in combination with navigation technology. Included in the overview are study type, tracking method, LUS probe, calibration method of LUS probe, registration method, images / visualization methods, and a brief mention of the main findings from the group.

- Martens (Martens et al., 2010): EM tracking, flexible LUS probe, ex vivo and in vivo studies, automatic multiple cross wire LUS probe calibration, landmark based coarse registration followed by surface registration using ICP. The group is developing a navigation system for laparoscopic liver interventions. They used LUS volume rendering, 3D view of preoperative data and tracked instruments, and 2D LUS image. Main result was a technical system ready for human trials.
- Sindram (Sindram et al., 2010): EM tracking, flexible LUS probe, phantom trainer, no calibration available, and no registration presented. They tried to determine whether using a magnetic tracking system improves accuracy during needle placement. They used stereoscopic 3D display and needle trajectory visualization. They reported perfect targeting of 5 mm lesions by novice surgeons.
- Solberg (Solberg et al., 2009): EM tracking, flexible LUS probe, phantom studies, 2D shape alignment calibration, and fiducial based registration (CT-model). The group is develpoing a navigated LUS system and assessed the accuracy of 3D LUS and EM tracking accuracy in a realistic OR setting. They demonstrated slicing, anyplane,

multivolume, volume rendering, and surface view visualization. They found the 3D LUS accurate in a phantom set-up, 1.6% to 3.6% volume deviation from the phantom specifications and little disturbance to EM field.

- Feuerstein (Feuerstein et al., 2009): EM and optical tracking, flexible LUS probe, system description, single wall calibration (Prager et al., 1998), and no registration described. They reported mainly on a method for correction of intraoperative magnetic distortion that can be applied to improve LUS based navigation. The overall goal was a 3D LUS system for augmented reality in laparoscopic surgery. No visualization method were described or demonstrated. They found that modeling the poses of the transducer tip in relation to the transducer shaft allowed them to reliably detect and significantly reduce EM tracking errors.
- Langø (Langø et al., 2008): EM tracking, flexible LUS probe, system description, 2D shape alignment calibration, and fiducial based registration (CT, patient). The publication was mainly a technical development (hardware and software) description of a navigation system for laparoscopy, including LUS component. They showed slicing, anyplane, multivolume, volume rendering, and surface view visualizations. The authors presented clinical feasibility from pilot trials.
- Hildebrand (Hildebrand et al., 2008): EM tracking, flexible LUS probe, ex vivo studies, and manual landmark registration (CT to physical space of porcine model setup). The group was developing a navigation system for laparoscopic liver therapy with focus on radio frequency ablation. They demonstrated 3D surface view of planning data, overlay of navigated needle and 2D LUS on 3D surface view of planning data. They found that advanced laparoscopic ultrasound skills are the basis for accurate RFA probe placement.
- Nakamoto, Nakada, Sato (Nakada et al., 2003; Nakamoto et al., 2008; Sato et al., 2001): EM tracking, in vitro and in vivo studies, 2D shape alignment calibration, and no registration method mentioned. The group showed 3D LUS based augmented reality visualization during laparoscopic surgery and demonstrated a calibration method for intraoperative magnetic distortion that can be applied during LUS acquisitions. LUS volume rendering was used as a visualization approach. They found that data acquisition time shortened with improved distortion correction. Their proposed method corrects magnetic distortion with an accuracy of 3 mm or less within 2 minutes.
- Konishi (Konishi et al., 2007): EM and optical tracking, flexible LUS probe, in vivo studies, 2D shape alignment calibration, and landmark based registration (CT-endoscopic views). They evaluated the usefulness and accuracy of a navigation system in an animal model. 3D LUS was overlaid on endoscopic view (augmented reality visualization) and vessel structures were displayed on preoperative CT data. They reported that the rapid calibration method was effective and it corrects magnetic distortion with accuracy of 2 mm.
- Hildebrand (Hildebrand et al., 2007): EM tracking, flexible LUS probe, ex vivo studies, no probe calibration available, and no registration method were mentioned. They evaluated an EM navigation system for laparoscopic interventions using a perfusable ex vivo artificial tumor model. Overlay of tracked instrument on 2D LUS image were performed. They concluded that laparoscopic ultrasound guided navigation is technically feasible.
- Estepar (Estépar et al., 2007; Estépar et al., 2007): EM tracking, in vivo studies, single wall calibration, and fiducial based registration (CT-LUS). Ultrasound based navigation system

for transgastric access procedures were described in the publication. Visualization was performed with 3D surface model from CT with tracked probe overlaid on the model. They were able to report successful navigation for transgastric access.

- Bao (Bao et al., 2004): Optical tracking, rigid side looker LUS probe, phantom studies, plane mapping calibration, and no registration method described. The group was developing a laparoscopic radiofrequency ablation guidance system. They demonstrated 3D LUS volume rendering and overlay of tracked instrument on 2D and 3D LUS image. Targeting accuracy was reported to be 5-10 mm (size of error in missing targets).
- Kleeman, Birth (Birth et al., 2004; Kleemann et al., 2006): EM tracking, in vivo studies, no probe calibration available, and no registration mentioned. The authors wanted to transfer navigated parenchyma dissection from open surgery to the laparoscopic technique. They utilized navigation line overlaid on the 2D LUS with a function to indicate out of plane dissection. They showed that this was feasible for achieving increased precision in laparoscopic liver dissection.
- Leven (Leven et al., 2005): EM tracking, rigid LUS probe, ex vivo studies, single wall calibration, and no registration described. Their goal was to develop a versatile telerobotic surgical system useful for multiple procedures. They used 2D LUS viewed as a picture-in-picture insert or as an overlay on endoscopic video. 3D LUS overlay on endoscopic video was also implemented. They found that experienced surgeons performed better with freehand ultrasound. Experienced and novice surgeons performed similarly with robotic assistance and robotic assistance required longer time for surgeons to identify lesions.
- Krucker (Krucker et al., 2005): EM tracking, flexible LUS probe, phantom studies, single point cross wire calibration, and fiducial based registration (CT to LUS). They used EM tracking to register LUS to preoperative CT. They performed overlay of LUS with preoperative CT and the registrations could be visualized together with tracked instruments. Fast and accurate registration was obtained using a tracked laparoscope with EM tracking.
- Bao (Bao et al., 2005): Optical tracking, rigid side looker LUS probe, phantom studies, plane mapping calibration (Bao et al., 2004), and fiducial based registration (CT to LUS) was used. The authors attempted to perform registration of ultrasound to CT for image-guided laparoscopic liver procedures. They used various CT renderings and visualization of 2D LUS placed in 3D CT. They found an average localization error of 5.3 mm.
- Ellsmere (Ellsmere et al., 2003; Ellsmere et al., 2004): EM tracking, flexible LUS probe, in vivo studies, single point cross wire calibration, and anatomical landmark based registration (CT to LUS). They demonstrated on the development fo a system for orienting and visualizing LUS images better. They used ultrasound 2D images and volume rendering visualization with respect to CT angiograms. They concluded that visual orientation information to the surgeon significantly improved the ability to interpret LUS images.
- Wilheim (Wilheim et al., 2003): EM tracking, flexible LUS probe, in vitro and in vivo studies, no calibration or registration method were mentioned. The authors presented an evaluation of an EM navigated LUS and a comparison of 3D navigated transcutaneous ultrasound and 3D CT. They used LUS volume rendering visualization. They found that navigated LUS was superior to both transcutaneous 3D ultrasound and 2D LUS.

- Harms (Harms et al., 2001): EM tracking, linear flexible LUS probe, ex vivo and in vivo studies, no calibration or registration method were mentioned. The group performed 3D ultrasound of liver lesions, comparing 3D LUS to 3D CT. They used 2D slicing and LUS volume rendering visualization. They found that LUS slightly underestimated the volume of the region of interest and that LUS was more accurate than transcutaneous ultrasound.

In summary, these publications show that navigated LUS has several advantages in laparoscopic guidance compared to conventional 2D LUS, especially due to the orientation challenges. The further advancement of soft tissue navigation requires surgeons, engineers, and perhaps radiologists, to collaborate more closely, inside and outside the OR. Specific surgical procedures have to be identified, where current technological possibilities will fulfill user demands as a tool for obtaining improved patient care. From the literature it seems that authors have targeted laparoscopic liver therapy guidance as one of the most important applications, where the demands for navigated LUS is emphasized. There is a general lack of assessment protocols that can be used to evaluate the technological solutions to show a potential clinical benefit to the patient and/or the surgical staff. This is of course connected to the fact that most publications are in early development phases. Nevertheless, such clinical study protocols should be developed early during research to enable possibilities for proper clinical assessment of navigated LUS.

2.6 Image fusion

3D ultrasound integrated with preoperative images can help interpreting the content of the LUS images, as well as the position, in correspondence with surrounding anatomy. We have previously mentioned that image fusion techniques can make it easier to perceive the integration of two or more volumes in the same display (monitor), compared to mentally fusing the two volumes that are displayed on separate monitors (Solberg et al., 2009). Ideally, relevant information should not only include anatomical structures for reference and pathological structures to be targeted (CT/MRI and ultrasound tissue), but also important structures to be avoided, like blood vessels (depicted with CT/MR contrast, ultrasound Doppler). We believe that such features will be important when visualizing LUS data together with preoperative CT data from a patient during surgery. The ultrasound data will show updated information that the surgeon relies on during surgery, while advantages from preoperative data, such as better overview and understanding of the anatomy and pathology, are also considered. Nevertheless, this type of multivolume visualization demands fast rendering algorithms, e.g. using GPU. Such methods are becoming more available as GPU application interfaces are being developed and tested on various brands of GPU and computer system platforms. Multimodal imaging may be achieved with 2D slices or 3D surface models also, requiring less processing power than multivolume 3D renderings.

2.7 Virtual endoscopy

A technique that could have potential in laparoscopy is “virtual endoscopy” (Shahidi et al., 2002) or image-enhanced endoscopy. This approach uses computer graphics to render the view seen by a navigated video laparoscope inside the abdomen, based on a representation of the cavity calculated from preoperative MRI or CT images. Using segmented structures (e.g. tumor and vessels) overlaid the real laparoscopic video is often termed augmented reality or multimodal image fusion visualization (Konishi et al., 2007; Scheuering et al., 2003). Such a view may help the surgeons to quickly interpret important information beyond the surface of the organs as seen by the conventional video camera. More research into segmentation of anatomic and pathologic structures may improve the usefulness of e.g. overlay or side-by-side view of virtual endoscopy and tracked laparoscopic images. Combining this with LUS could help detect organ shifts and also augment the scene view further for the surgeon, providing more details in depth and in real time.

To make it easier to understand what is beyond the surface of organs as seen in the laparoscope during surgery, navigation and image fusion can be used as shown in figure 4. Segmented structures from 3D CT can be gradually overlaid the video laparoscopic image, showing important information about lesion and vessel position inside the organ. This may improve the surgical approach both due to optimal resection and the avoidance of bleedings.

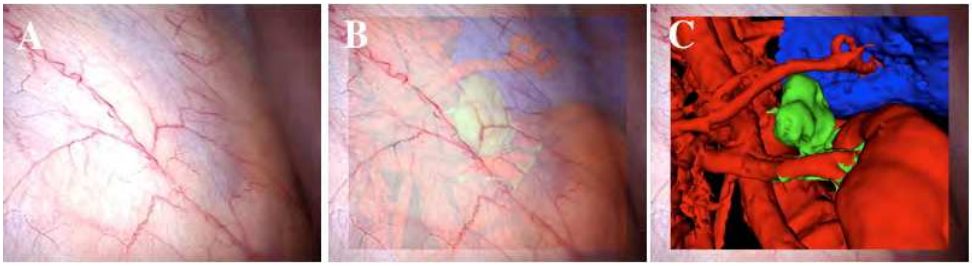

Fig. 4. Augmented reality example showing segmented structures from a CT volume overlaid the video laparoscope image, making it possible to see beyond the surface of the organ. This makes it possible to perform optimal resection planning during a laparoscopic adrenalectomy.

2.8 Challenges - Organ shifts and tissue deformations

The main challenges of navigated surgery of soft tissues are shifts due to manipulation and gravity. Movement of anatomy such as that caused by blood flow pulsation, breathing and induction of pneumoepritoneum in laparoscopy could mean that the preoperative images no longer match the intraoperative target anatomy of the patient. We have found that pneumoperitoneum causes a shift of the liver in an animal model (pig) of up to approximately 3 cm (no significant deformation, unpublished data). Pulsation and breathing causes smaller but repetitive displacements in anatomy. Important approaches in order to solve the problem of displaced anatomy due to surgical manipulations, probably the largest shifts, are navigation technology combined with LUS. Intraoperative ultrasound is becoming routine in some surgical disciplines, e.g. neurosurgery (Unsgaard et al., 2006). Another approach is to update or morph preoperative data based on intraoperative ultrasound (Bucholz et al., 1997; Reinertsen et al., 2007) to better match the intraoperative situation. This is a computationally expensive method, and also prone to errors difficult to detect, i.e. changes to parts of the volume cannot be easily verified during the procedure. Shifts detected by LUS could for instance be utilized to colour code preoperative data voxels to make the surgeon aware of deformations and shifts.

In laparoscopy, we have experienced that when the lesion is located in the retroperitoneum, only minor shifts in anatomy are detected (Mårvik et al., 2004), which may be compensated by using 3D ultrasound to acquire updated maps of the anatomy. Nevertheless, tissue motion and deformations during surgery require continuous correction and update of images for constant and reliable navigation accuracy. Freehand 3D ultrasound systems can be extended to 4D ultrasound images and these 4D ultrasound images can be used to determine the liver motion and deformation caused by respiration by using a non-rigid registration method (Nakamoto et al., 2007).

Application of soft tissue modeling methods is becoming a promising manner to enable continuous motion compensation during navigated surgery (Carter et al., 2005; Hawkes et al., 2005). Mathematical models are able to describe tissue behavior to a certain degree of accuracy during a procedure based on various parameters estimated for the organ. Rigid based deformation techniques can only describe global changes, while spline-based approaches can also capture local variances of tissue deformation by varying the position of a few control points (landmarks). Such methods are also used in virtual simulators for training laparoscopic skills (Kühnapfel et al., 2000). 4D models that use gating techniques or tracking technology to track the patients’ breathing and/or blood pulsation enable image-guided therapy with higher accuracy and security.

2.9 Challenges - EM tracking accuracy

One of the major challenges with EM tracking is that it is vulnerable to disturbances from ferromagnetic interference sources in the surroundings, which may influence the accuracy of the system. Several groups have performed static and dynamic accuracy evaluations of different EM and optical trackers (Frantz et al., 2003; Nafis et al., 2006; Nafis et al., 2008; Schmerber & Chassat, 2001), which provide useful data for accuracy comparisons. EM trackers in the OR are subjected to distortion from several sources, and the impact of the level of interference may vary between the different trackers. A number of papers deal with distortions to the EM tracking systems from metals (Hummel et al., 2005; Kirsch et al., 2006; Nafis et al., 2006), surgical instruments (Hummel et al., 2002; Schicho et al., 2005), ultrasound probes (Hastenteufel et al., 2006; Hummel et al., 2002; Schicho et al., 2005), OR tables (Hummel et al., 2005; Nafis et al., 2008) and OR environments (Wilson et al., 2007). In summary, these papers also show that the EM trackers robustness regarding distortion sources have improved significantly over the latest years. Using EM tracking in a conventional OR equipped for laparoscopy, distortions would normally be in the milimeter range, while in ORs with special equipment like a C-arm inside the surgical field, distoritons may be in the centimeter range (Wilson et al., 2007) (and own unpublished data).

One group (Hastenteufel et al., 2006) showed that 2D ultrasound probes does not affect EM tracking system accuracy significantly compared to the more complex 3D ultrasound probes when using the Flock of Birds® (Ascension Technology, USA) tracking system. However, they found that the 2D probes significantly affected the Aurora® (NDI, Canada) tracking system accuracy. This is most likely due to the fact that Aurora is based on alternating current technology and Flock of Birds uses pulsed direct current technology, so they will have different advantages and drawbacks when used in various environments. Schicho *et al* (Schicho et al., 2005) also showed that a 2D ultrasound probe affects EM tracking accuracy in an ideal setup where the ultrasound probe is the only distortion factor. We have shown previously that the error introduced by a LUS probe does not add significantly to the error of the Aurora tracking system, compared to the contribution from the OR table and surrounding error sources in an intraoperative experimental setup (Solberg et al., 2009). The largest distortion factor in our OR setup was most likely the OR table, being quite close to the Aurora field generator and sensor. Although equipment in the OR may affect EM positioning accuracy, this challenge can be reduced and the overall benefit of navigated 3D ultrasound using EM tracking seems sufficient to be further explored in laparoscopy.

It is therefore important to assess the accuracy, not only for each system, but also for each new location where the system is to be used. If there are disturbances that are constant and may be properly characterized, they may be compensated using static correction schemes (Chung et al., 2004; Kindratenko, 2000). These correction schemes require a set of distributed measurements within the tracking volume and corresponding reference measurements to compute a distortion function.

Since the interference depends on the surroundings, it must be characterized for each new location and the correction scheme must be adapted accordingly. In addition, if the environment changes during the procedure, e.g. by introduction of additional equipment, this must be taken into account. One of the earlier attempts to compensating dynamic errors intraoperatively involved focusing on the region of interest alone to apply the distortion model (Konishi et al., 2007; Nakamoto et al., 2008). A more recent approach to detect and reduce dynamic EM tracking errors intraoperatively makes use of a tracking redundancy and a model based approach instead of a pre-computed distortion function (Feuerstein et al., 2009).

2.10 Other error sources

In addition to tracking errors, probe calibration is an important error source in ultrasound based image guided surgery. Incorrect probe calibration implies that an image point will be displaced from its "true" position in the navigation system display. If the probe is shifted/rotated, the same shift/rotation occurs to the displacement. Probe calibration may be related to various error sources (Mercier et al., 2005) and is perhaps the largest source of error in 3D freehand ultrasound acquisitions (Lindseth et al., 2002). Additional sources of error in navigated LUS are:

- Sensor attachment repeatability. EM trackers are usually integrated into the probe so that this is not an important factor if they are made in such a way that a unique adapter is fitted to each probe.
- Reference frame attachment to the patient and/or OR table. The OR team may easily bump into this equipment, displacing it relative to the patient.
- Synchronization in time between position data and ultrasound images during acquisition (3D freehand scanning) and navigation.
- Sound speed variations in tissue, which is less important in relatively homogenous soft tissues. This parameter is especially important when reconstructing freehand tracked 2D ultrasound slices into a 3D volume.
- Thickness of the ultrasound plane, which could lower the quality of the 3D volume and cause less accurate determination of structure positions, especially at large depths in the images.

The delicacy, precision, and extent of the work the surgeon can perform based on image information, rely on his/her confidence in the overall clinical accuracy and the anatomical or pathological visualization. The overall clinical accuracy in image-guided surgery is the difference between where a surgical tool is located (orientation and position) relative to a structure as indicated in the images presented to the surgeon, and where the tool is actually located relative to the same structure inside the patient. This overall accuracy is difficult to assess in a clinical setting, due to the lack of fixed and well-defined landmarks inside the patient that can be reached accurately by a tracked instrument. One solution is to estimate the system's overall accuracy in a controlled laboratory setting using precisely built phantoms. In order to conclude on the potential clinical accuracy, the differences between the clinical and the laboratory settings must be carefully examined (Lindseth et al., 2002). It is crucial that the user of image based navigation systems is aware of the potential error sources and limitations in accuracy, e.g. expected accuracy and maximum differences in real position of instrument tip versus position displayed by the navigation system.

3. Summary

Being a relatively new area of research, it is interesting to note that the number of active research groups in this field seems to be 10-11. Based on the overview, we have been able to identify the key issues and also spot the future possibilities in the area to help improve the surgical scenario in the OR. Based on our literature findings and almost two decades working with surgeons on developments for advanced laparoscopic surgery, a complete system designed for navigated LUS could be used according to the following clinical scenario:

- The preoperative data is imported and reconstructed into 3D; several structures and organs are segmented automatically (e.g. vessels from contrast CT scan) or semi-automatically (e.g. seed point set inside the tumor).
- A quick plan is made from the visualization in the navigation system just prior to surgery, perhaps in the OR during other preparations.
- Registration is performed without fiducials using a pointer (orientation of patient) and two landmarks for a rough first approximation.
- Before mobilizing the target organ (e.g. the liver) a 3D LUS scan of major vessels near or around the tumor is performed.
- The LUS images are reconstructed into 3D and an automatic vessel based registration (CT-to-ultrasound) is performed to fine tune the registration.
- Augmented reality visualization, e.g. on/off overlay of preoperative data and LUS on the video laparoscope view is preformed as needed by the surgeons during the procedure
- 3D LUS scans are updated a few times during the procedure, while the real time 2D LUS image is available as either:
    - A full size image with a corresponding indication in a 3D CT rendering of its orientation and position, or
    - An overlay on the video laparoscope view with or without elements from the CT data (segmented structures for instance).

For rigid organ navigation, a single preoperative scan, highly accurate tracking (optical), and rigid surgical tools are sufficient to guide the procedure. However, for soft tissue navigation, additional tools are needed due to deformation and mobile organs in the abdominal cavity, resulting in more complex systems and additional devices in the OR. LUS can provide real time behind-the-surface information (tissue, blood flow, elasticity). When combined with advanced visualization techniques and preoperative images, LUS can enhance an augmented reality scene to include updated images of details, important for high precision surgery thus enhancing the perception for surgeons during minimal access therapy. LUS integrated with miniaturized tracking technology is likely to play an important role in guiding future laparoscopic surgery.

4. Acknowledgments

This work was supported by SINTEF, the Ministry of Health and Social Affairs of Norway through the National Centre of 3D Ultrasound in Surgery (Trondheim, Norway) and the project 196726/V50 *eMIT* (*enhanced Minimally Invasive Therapy*) in the FRIMED program of the Research Council of Norway.

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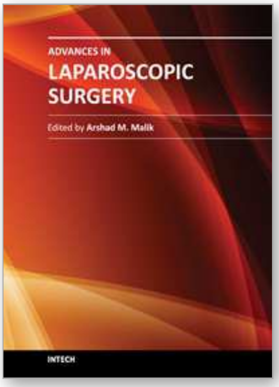

Advances in Laparoscopic Surgery
Edited by Dr Arshad Malik

ISBN 978-953-307-933-2
Hard cover, 148 pages
Publisher InTech
Published online 01, February, 2012
Published in print edition February, 2012

Laparoscopic surgery, also called minimal access surgery, has revolutionized the field of surgery over the past few years. It has gained worldwide popularity and acceptance by surgeons and patients alike. Minimal scarring, less pain, and shorter hospital stay are the main reasons behind the global appeal of this novel technique. There has been a tremendous improvement in the technique, as well as in the instruments. The technique has passed through the stages of simple laparoscopic surgery to advanced levels, where more complicated procedures are being successfully attempted. The recent introduction of robotic surgery is also gaining popularity, in additional to single port laparoscopic surgery (SILS), which can be scarless surgery. Most of the surgical procedures, which were considered contraindication for the laparoscopic approach, have eventually become the most common and acceptable indications today. This book is intended to provide an overview of the most common procedures performed laparoscopically, as well as some recent advancements in the field.