# Imaging Support of Minimally Invasive Procedures

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**Abstract.** Since the discovery of x-rays, medical imaging has played a major role in the guidance of surgical procedures, and the advent of the computer has been a crucial factor in the rapid development of this field. As therapeutic procedures become significantly less invasive, the use of pre-operative and intra-operative images to plan and guide procedures has gained increasing importance. While image-guided surgery techniques have been in use for many years in the planning and execution of neurosurgical procedures, more recently endoscopically-guided approaches have made minimally invasive surgery feasible for other organs. The most challenging of these is the heart. Although some institutions have installed intra-operative, real-time MRI facilities, these are expensive and often impractical. So a major area of research has been the registration of pre-operative images to match the intra-operative state of organs during surgery, often with the added assistance of real time intra-operative modalities such as ultrasound and endoscopy. This paper examines the use of medical images, often integrated with electrophysiological measurements, to assist image-guided surgery in the brain for the treatment of Parkinson's disease, and discusses the development of a virtual environment for the planning and guidance of epi- and endo-cardiac surgeries for coronary artery bypass and atrial fibrillation therapy.

## 1 Introduction

Minimally invasive surgical procedures are becoming increasingly common, and as a result, the use of images registered to the patient, is a prerequisite for both the planning and guidance of such operations. While many invasive procedures, (traditional coronary artery bypass for example) require relatively minor surgical intervention to effect the desired therapy or repair, the patient is often severely physically traumatized in the process of exposing the site of the therapeutic target. In one sense the objective of minimally invasive approaches is to perform the therapy without the surgery!

Minimally invasive techniques have been in use now for many years, particularly in the brain and skeletal system. The targets in these cases are relatively rigid, making the process of registering pre-operative images to the patient fairly straightforward. For other organs, for example the heart, liver, and kidney, registration is not as simple, and it is these organs that present the major challenges for imaging during minimally invasive surgery.

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## 2 Neuro Applications

### 2.1 Frame-Based Stereotactic Deep-Brain Surgery

Computerized surgical planning systems made their debut in the early 1980's using simple programs that established coordinate systems in the brain based on frame-based fiducial markers. This approach rapidly evolved to allow images from multiple modalities to be combined, so that surgical planning could proceed using information from a combination of MRI, CT, and angiographic and functional images. Such multi-modality imaging was considered important for certain procedures, such as the insertion of probes or electrodes into the brain for recording or ablation, and the ability to simultaneously visualize the trajectory with respect to images of the blood vessels and other sensitive areas. Multi-modality imaging enabled the pathway to be planned with confidence [1;2]. Much of stereotactic neurosurgery was concerned with procedures involving the safe introduction of probes, cannulae or electrodes into the brain.

### 2.2 Frameless Stereotaxy

Because the attachment of a frame to the patient's skull is itself invasive, there has been a general desire to eliminate the use of the frame from the procedure. However, without the frame to provide the fiducial markers, some other type of reference system must be employed to register the patient to the image(s). A commonly used registration method is point-matching, where homologous landmarks are identified both in the images and on the patient. Unfortunately, some variation in the identified locations of the landmark points on the patient is always present, and it is difficult to pinpoint exactly the same locations within the patient's three-dimensional image. Point matching is often employed in conjunction with surface-matching, which is achieved using the probe to sample points on the surface of the patient, and then determining the best match of this point-cloud to an extracted surface from the 3-D patient image. Under ideal conditions, accuracy approaching that available with stereotactic frames can be achieved [3].

### 2.3 Integration of Physiological Information with Images

A common treatment for Parkinson's disease involves the ablation or electrical stimulation of targets in the deep brain, either within the thalamus, the sub-thalamus, or the globus pallidus. The standard imaging modality for guiding the surgical treatment of targets in the deep brain is a T1-weighted volumetric MR image. This image however does not show the affected parts of the brain directly, nor does it demonstrate the deep-brain nuclei that constitute the targets for such therapy. Other means must be used to define the target areas within the otherwise homogeneous regions. Approaches to solve this problem include the use of atlases mapped to the patient images, using linear, piece-wise linear, or non-rigid registration. This is often complemented with information gained from electrophysiological exploration of the target area, together with anatomical data provided by MRI, CT, or angiography. Mapping the electrophysiological responses recorded during such procedures onto the 3-D anatomical images of the patient helps the surgeon navigate towards the desired target. Moreover, a database of such responses, normalized through non-rigid image registration to a standard data space, can be integrated with the patient's 3-D MRI to assist the surgeon by predicting the likely target for creating a therapeutic lesion [4]. A typical example of electrophysiology integrated with 3D MRI for guiding the surgeon to the target in the treatment of Parkinson's disease is shown in Figure 1.

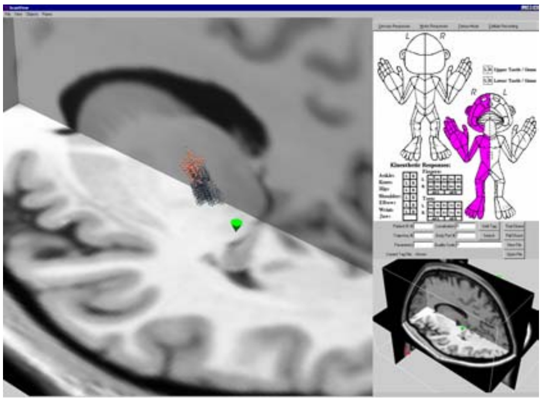

**Fig. 1.** Example of electrophysiological database acquired from multiple patients, and integrated with 3D MRI of patient. The figure in the upper right is the interface whereby the user selects the body-region associated with the stimulus/response data being entered or displayed

## 2.4 Brain-Shift Compensation

If the entry point for the target within the brain is inserted into the otherwise intact skull, the brain may be treated as a rigid body and pre-operative images, registered to the patient, are appropriate for guidance during the procedure. In the presence of a craniotomy however, significant brain shift occurs, and the pre-operative images no longer represent the intra-operative morphology of the brain. Various approaches have been used to solve this problem, from the use of MR imaging systems that are somewhat "operating-room unfriendly", to intra-operative ultrasound integrated with the image-guidance protocol. Updating of neuro MR volumes using intra operative ultrasound continues to be an active research topic in our laboratory and others.

As the reach of minimally-invasive surgery extends beyond the brain, so the demands on image processing to accommodate procedures in other organ systems increases. Most of these procedures involve non-static states, being affected by blood-pressure changes, breathing or the interaction with surgical tools. If image-guidance is to be used in these situations, realistic models that are synchronized in space and time with the actual patient organ are required.

## 3 Application to the Heart

In being an appropriate candidate for image-guided surgery, the heart is probably at the opposite end of the spectrum from the brain. Despite this, we were motivated to attempt the goal of developing a dynamic cardiac model for planning and guidance purposes by our surgical colleagues who are performing robotically-assisted coronary bypass surgery, as well as electro-ablative procedures within the left atrium.

### 3.1 Bypass Surgery

Many conventional cardiac surgical procedures require a sternotomy and a cardiopulmonary bypass procedure, which subjects patients to significant trauma and lengthy hospital stays. Recently, minimally invasive direct coronary artery bypass (MIDCAB) procedures have been introduced, performed via instruments introduced into the chest via trochars and guided endoscopically. Such techniques are making a significant impact on cardiac surgery, but because of the extreme difficulty in manipulating the instruments at the distal ends of the trochars, several surgical teams have begun to perform coronary bypass surgery on the beating heart in the intact chest, using tele-operated robots inserted into the chest via intercostal ports [5].

In spite of the sophistication of these robotically assisted systems, the use of medical images in the planning of the procedure is mostly limited to conventional chest-radiographs and angiograms. The use of such simple images makes it extremely difficult to plan the positions for the entry ports between the ribs, and provides minimal guidance during the procedure.

While minimally invasive and robotically assisted approaches are enjoying increasing application, the potential benefits have not yet been fully realized. In the absence of a more global perspective of the target organ and its surroundings, the spatial context of the endoscopic view can be difficult to establish. Other intrinsic limitations of the endoscope include its inability to “see” beneath the surface of the target, which is often completely obscured by bleeding at the surgical site. To assist the planning and guidance of such procedures, there are a number of reports [6;7;8] describing the development of static virtual modeling systems to plan cardiac surgical procedures.

### 3.2 Atrial Fibrillation Surgery (AFS)

Arrhythmias have long been controlled with minimally invasive approaches, in both the operating room and in the electrophysiology (EP) laboratory using catheter techniques.

Atrial fibrillation is difficult to treat using catheter techniques, but a conventional surgical approach is considered excessively invasive. Colleagues at the London Health Sciences Centre, London, Canada, have recently developed a minimally invasive technique that permits ablative therapies to be performed within the closed beating heart, using instrumentation introduced through the heart wall. This duplicates the surgical procedure that is otherwise performed using an open heart technique, with life-support being provided by a heart-lung machine. However, this approach requires the support of image guidance, to integrate both anatomical and electrophysiological data, highly analogous to the neuro-physiological mapping approaches described earlier.

Unlike during epicardial procedures, an endoscope cannot be used to navigate inside the blood-filled atrium. A fully minimally invasive approach requires the use of surrogate images based on a simulated heart model dynamically mapped to the patient. This model must in turn be complemented with the intra-procedure EP data mapped onto the endocardial surface and integrated within the virtual planning and guidance environment.

## 4 Towards a Virtual Cardiac Model

Effective image guidance for these surgical procedures is challenging and demands a cardiac model that is registered to the patient in both space and time. The image-guided surgery laboratory at the Robarts Research Institute in London, Canada is currently engaged in a project to achieve this goal via the following steps:

1. The creation of a dynamic cardiac model
2. Registration of the model to the patient
3. Synchronization of the model to patient
4. Integration of patient and virtual model
5. Integration of registered intra-cardiac and intra-thoracic ultrasound
6. Tracking of tools and modeling them within virtual environment.

### 4.1 Dynamic Cardiac Model

Dynamic imaging using both MR and CT has become a common feature of contemporary medical imaging technology, but it is difficult to acquire high quality images at every phase of the cardiac cycle. However, during end-diastole, one can obtain a quasi-static 3D image of relatively high quality. While images acquired at other phases of the cardiac cycle are noisier and often contain motion artifacts, they nevertheless contain much of the information necessary to describe the motion of the cardiac chambers throughout the heart cycle. Capturing this information and applying it to the high-quality static image allows an acceptable dynamic model to be created. This behavior has been exploited by Wierzbicki *et al.* [9] to generate high quality dynamic image models from patient data that can be incorporated in a dynamic virtual model of the heart within the thorax.

Within such a virtual environment, it is also important to integrate data from tracked real-time imaging tools, such as endoscopes and ultrasound probes. Our work in this area has recently been reported by Szpala *et al.* [10] who demonstrated that the dynamic dataset representing the virtual cardiac model could be integrated with the real-time endoscopic image delivered by a tracked endoscope.

Our work continues to refine these techniques, as well as to address the problems of image-to-patient registration; tracking intra cardiac and intra thoracic ultrasound, the mapping of cardiac electrophysiology into the model environment, and the repre-senttation of tracked tools within the virtual environment.

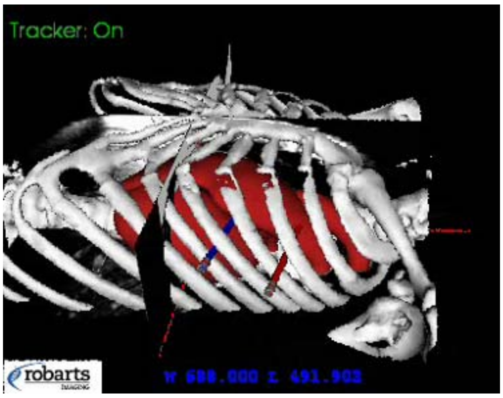

**Fig. 2.** Virtual model of beating heart within thorax with integrated representation of robotic probes.

## 5 Challenges

There are many challenges associated with this endeavour, and they are not unique to the application for cardiac therapy. The most pressing is perhaps the development of means to rapidly deform the dynamic organ models in response to the intervention of a therapeutic instrument. This entails not only endowing the model with sufficiently realistic characteristics to allow it to behave appropriately, but also to ensure that performance is not compromised in the process. Finite element representations of organs have been proposed by many groups, and well characterized models can predict tissue behaviour accurately. However, it is acknowledged that finite element model (FEM) techniques are often orders of magnitude too slow for real-time operation, and that alternative approaches must be developed. One method is to parameterize the behaviour of tissues based upon observed responses of actual or finite-element models of organs to sample stimuli [11;12]. Another challenge will be to enable the updating of the model environment rapidly as intra-operative imaging detects the changes during the procedure. This will require accurate tracking of the intra-operative imaging modality, rapid feature mapping between the image and the model, and local deformation of the model to match the image. While these operations require a large computational overhead of multiple simultaneous execution modules, we believe that the evolving levels of readily-available computational power will be sufficient to accomplish these goals in the near future.

On a broader front, a working group discussing the future of intraoperative imaging at a recent workshop[1] held in Maryland, USA April 18-20 2004, identified a number of challenges that must be met before the ideas presented here, and the ubiquitous use of image-guided intervention in general, can become established on a routine basis. It was observed that most operating rooms in the world are not even equipped with PACS, let alone the infrastructure to bring sophisticated 3D and 4D imaging into the OR suite; that we still lack the tools to rapidly pre-process images (i.e. segment,

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[1] OR 2020 http://www.or2020.org/

mesh) in an automatic pipeline fashion; that metrics for success of both the technology and outcomes related to new image-guided surgical procedures are poorly defined at present, and that there remains a great deal of incompatibility across manufactures with respect to standard interfaces to equipment.

The workshop presented a number of "Grand Challenges" that the members considered on which industry should focus to enable these technologies:

1. the development of integrated displays that can inherently handle multiple modalities in multiple formats simultaneously;
2. that systems be designed to accommodate inherent tracking and registration across modalities, tools, endoscopes, microscopes;
3. that advanced non-rigid image registration, at both the pre-op and intra-operative phases of the procedure be developed together with appropriate error measures; and
4. that OR-destined imaging systems should be developed from the ground up, rather than as diagnostic systems retrofitted in the OR.

I believe that these issues MUST be addressed in a coordinated fashion, with full participation of industry, if we as a community are to make significant progress in the development of image-guidance to enhance minimally invasive procedures.

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