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In Brief

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Surgeons have traditionally performed procedures to treat diseases by gaining direct access to the internal structures involved, and using direct visual inspection to diagnose and treat the defects. Much effort has gone into identifying the most appropriate incisions and approaches to enable full access inside body cavities, specific organs or musculoskeletal structures. Imaging has traditionally been used primarily for pre-operative diagnosis and at times for surgical planning. Intra-operative imaging, when used, was meant to provide further diagnostic information or to assess adequacy of repair. In most cases X-ray static images or fluoroscopy has been used in the operating room. As the application of less invasive procedures has progressed, other imaging technology has been applied in an effort to address the limitations of simple X-ray or fluoroscopy. Computed tomography, magnetic resonance imaging, ultrasound, nuclear radiographic imaging, and optical imaging have been introduced to provide the information required to plan and perform complex interventions inside the body without the need for direct open visual inspection.

In parallel with the developments in imaging modalities, endoscopic surgery has advanced with the introduction of rigid and flexible scopes equipped with video cameras to magnify and display the image obtained. Advances in optics and digital electronics have combined to provide unparalleled image quality even with small diameter scopes resulting in an explosion of endoscopic procedures involving virtually every structure in the body. The only real limitation to imaging has been the inability to see or “image” through opaque structures since the irradiating or “illuminating” energy provided through the scope, has been almost exclusively visible light. This limitation has confined endoscopic surgery to areas where a natural body cavity or physical space can be accessed with a scope and instruments, and filled with non-opaque medium such as a gas or clear fluid. Despite these limitations, optical endoscopy has revolutionized the way many surgical procedures are done, and has spawned a whole industry of instrument manufacturers that, in conjunction with surgeons, design task specific tools capable of entering the desired body cavity along side the scope. It has also forced surgeons to develop new techniques utilizing these specialized instruments for carrying out a wide variety of operative procedures.

For most endoscopic procedures, optical imaging provides sufficient information to guide the various steps of the surgical procedure including: identification of target lesion, instrument navigation from entry point into the body to the target, identification of important anatomic structures, view of tissue-instrument interaction in real-time, and real-

time assessment of tissue reconstruction/manipulation. Along with the focus on imaging and instrument development, there is widespread recognition that there are major components common to all image guided procedures that have had to develop in parallel. These include: imaging modalities that provide the required information for successful achievement of the procedure, image displays with optimal resolution and ergonomics to facilitate workflow, aids to instrument navigation when the instrument, tissue target, or instrument-target interaction are not directly visible, and specialized surgical instruments and devices optimized for the task and modified for the type of imaging modality.

This review will cover each of these four topics (Imaging, Displays, Navigation, and Surgical Instruments) as they apply to the various imaging modalities. Our goal is to provide an overview of the current technology available or being developed with examples of clinical applications and areas of research and technology development. The importance of this field to practicing surgeons cannot be overstated as technological advances will likely enable performance of ever more complex procedures inside the body using minimal access techniques to limit collateral tissue injury and improve overall surgical results. Thus, for practicing surgeons, gaining an understanding of the basics concepts of this technology will become imperative to keep pace with innovations in minimally invasive surgery.

To obtain critical information regarding body structures for performing surgical procedures, beyond what is visible externally or by direct internal inspection, various forms of imaging are often required. The advantages of visible light endoscopy are high spatial resolution , real time imaging, and the ability to see not only the inner surface of cavities, but also structures such as instruments within the lumen of the cavity. The main limitation of optical endoscopy however, is the lack of penetration of the illuminating energy (visible light) into opaque tissue structures.

Traditionally X-ray imaging has been used as an adjunct or instead of optical imaging inside the body due to its ready availability, and a number of advantages over other imaging modalities including high spatial resolution, ability to penetrate all tissues, low cost, and its ability to guide interventions in real time, with and without the aid of contrast material. The disadvantages of X-ray imaging however, include poor differentiation between soft tissue structures, ionizing irradiation, and two-dimensional projection imaging, the latter being a significant limitation to navigating instruments within body cavities. The various other imaging technology options available to surgeons can be categorized on the basis of specific factors that may be of advantage for a particular procedure such as: *Spatial resolution*, defined as the ability to detect point targets as distinct, Degree of tissue penetration, Ability to differentiate tissue boundaries, ability to detect different tissue characteristics, Location of imaging energy source, and the availability of real time imaging, Use of ionizing vs. non-ionizing radiation to obtain the images

For real-time guidance of surgical procedures, imaging needs to provide information regarding the location of the target lesion, associated and nearby structures, the relationship of surgical instruments to the target, and do this in “*real-time*” or at least 25 frames per second. The capability of an imaging modality to provide this information depends ultimately on the physics involved in generating the image. To appreciate how each imaging

technique can be used in surgery, it is important to understand how the image is generated and what the advantages and limitations are for each technique

Instrument navigation refers to the ability to introduce or advance a surgical tool to a desired target within the body. Often the trajectory desired by the surgeon is dictated by the location of the target region with respect to other critical anatomic structures and whether there is a readily accessible route to that structure. The location of the instrument or tool with respect to anatomic structures is most commonly obtained by the imaging modality used to guide the intervention, but other methods of localization can also be used such as electromagnetic or infrared tracking of the tool tip. To date, a great deal of work has been published concerning image-based needle or instrument navigation using fluoroscopy, CT, and MRI, primarily for interventional radiologic procedures. For surgical procedures, due to the need for real time imaging to guide instrument navigation, X-ray fluoroscopy and ultrasound are two frequently used imaging modalities. With its ease of use and non-ionizing energy for imaging, diagnostic and therapeutic navigation with ultrasound is a standard part of modern medicine.

Ultrasound-based navigation poses two challenges however. The first is ultrasound's limited field of view. When anatomical details within an image are unfamiliar or unrecognizable the clinician can lose orientation and is unable to mentally align the current image within the anatomy. In the case of 2-dimensional imaging, images are often taken parallel to image planes commonly displayed in reference texts (i.e. axial, sagittal, and coronal). In many ultrasound applications, however, either the acoustic windows do not allow acquisition in these planes or probe motion is constrained such that the planes cannot be achieved. The second challenge with ultrasound based navigation is due to the distortions of the image of metal surgical instruments. These make it difficult for the clinician to know the precise relative position and orientation of instruments with respect to the tissue, which leads to uncertainty in the required instrument motions to achieve a task. Imaging artifacts arising from reverberation and side-lobe reflections can obscure tissue near the instrument and make it nearly impossible to identify the instrument tip in the image

To perform procedures inside the body without direct visual access to the target structures, a display system is required to convey the critical anatomic and functional information to the surgeon in a timely manner and with minimum interruption of the work flow. Depending on the task to be performed and the nature of the target, the challenge is to determine what information is needed, how it should be best displayed, and at what speed the information need to be updated. For example, in procedures manipulating structures that are rigid such as bone and cartilage, anatomic information obtained a priori can either be displayed for immediate viewing, or it can be registered to the body and displayed as an overlay on a real-time image. Examples of this are overlays of pre-operative MRI of the brain overlaid on the image of the skull to plan the location of a craniotomy. For soft tissue or moving structures such as blood vessels, the bladder, or the heart, a more dynamic system is required that provides the surgeon updated information as to the position of the target organ. Depending on the speed of motion of either the structure or the surgical tool interacting with the tissue, the frame rate should be appropriately high to permit understanding of the motion characteristics and to prevent inadvertent collision or injury to tissue.

The type of information required for the surgeon to carry out a procedure is task specific. For some procedures, the surgeon only needs anatomic information. For other procedures, functional information is required such as the area of prolapse in a valve leaflet causing regurgitation. In other procedures, metabolic information is helpful to determine the site of increased activity indicating malignancy, and with still others, capillary density and tissue perfusion is important. Given the wide range of information available, a display system must enable the surgeon to correctly decide the location of the problem and to evaluate the effectiveness of the intervention. Often this information is obtained from different imaging modalities such as CT and MRI along with fluoroscopy or ultrasound. These images all need to be co-registered to the anatomic target for accurate overlay, and an easily understandable image or set of images needs to be provided to the surgeon.

The option of collecting 2D versus 3D data sets may be available and, for 3D data, there is the question of whether image visualization or rendering should be in 3D or 2D. The fourth dimension, time, also can be critical, particularly when working on rapidly moving structures such as the heart. Thus the science of information display encompasses many areas including display hardware, software development, graphical user interfaces and human factors to design efficient interfaces.

With any endoscopic procedure surgical instrument must be designed to navigate within the confined spaces of the operative field, but image guided surgery also requires the ability to detect the location of the surgical tool. Furthermore, for image guided interventions, the instrument must be made of material that is compatible with the imaging modality. To navigate complex trajectories, instrument flexibility and steerability are very desirable features. *Dexterity*, or the ability to smoothly manipulate tool position and orientation with as many degrees of freedom as possible, is also an essential feature for most endoscopic procedures. The issues in surgical instruments designed for image guided surgery include: rigid versus flexible tools, steerability and dexterity, compliant instruments, motion compensation tools, imaging-compatible tools, and multifunctional tools. Finally, the surgical tool itself can be an aid to navigation for image based segmentation and tracking, and as an imaging device or probe.

Image-guided surgery is the process of adapting sophisticated imaging technology to carry out surgical interventions inside the body that would normally require open procedures with direct inspection of the target area. For the surgeon to take full use of available technology, they must first understand the strengths and limitations of the various imaging modalities. They must also be willing to develop procedures that incorporate the imaging information, and utilize specialized instruments that are optimized for these procedures. As the technology advances and navigational aids improve, surgeons will be able to undertake ever more complex repairs not only inside body cavities but also inside solid organs and even rapidly moving organs such as the heart.