Chapter 1

Overview and History of Image-Guided Interventions

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Abstract

Although the routine use of image-guided intervention (IGI) is only about 20 years old, it grew out of stereotactic neurosurgical techniques that have a much longer history. This chapter introduces stereotactic techniques and discusses the evolution of image-guided surgical techniques enabled by the introduction of modern imaging modalities, computers, and tracking devices. Equally important in the evolution of this discipline were developments in three-dimensional (3D) image reconstruction, visualization, segmentation, and registration. This chapter discusses the role that each has played in the development of systems designed for IGI. Finally, a number of challenges are identified that currently are preventing IGI to progress.

1.1 Introduction

At the time of writing, the modern embodiment of the field of image-guided intervention (IGI) is approximately 20 years old. Currently, the general task of IGI can be subdivided into five smaller processes and a handful of general concepts. The subprocesses are to

1. gather preoperative data, generally in the form of tomographic images;
2. localize and track the position of the surgical tool or therapeutic device;
3. register the localizer volume with the preoperative data;
4. display the position of the tool with regard to medically important structures visible in the preoperative data; and
5. account for differences between the preoperative data and the intraoperative reality.

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Underlying IGI are two fundamental concepts:

1. three-dimensional position data can be used to guide a physiological or medical procedure and
2. path, pose, and orientation make the problem at least six dimensional.

Although IGI is only 20 years old, the concepts and subprocesses have been developed, tested, and refined for over a hundred years. It also is interesting to note that the first known medical application of x-ray imaging was taken with therapeutic, not diagnostic, intent. A mere 8 days after the publication of Roentgen's first paper on x-ray imaging in 1895, J. H. Clayton, a casualty surgeon in Birmingham, England, used a bromide print of an x-ray to remove an industrial sewing needle from a woman's hand [Burrows 1986]. Barely a month later, John Cox, Professor of Physics at McGill University in Montreal [Cox and Kirkpatrick 1896], successfully removed a bullet from the leg of a victim based upon the radiograph that had been made of the limb. Not only was the projectile successfully removed on the basis of the radiograph, it was later used as evidence during a suit against the man who had shot the victim.

1.2 Stereotaxy

Horsley and Clark [1908] published a paper on a device that embodied several concepts and methods central to IGI 12 years after Clayton's landmark procedure. This device was a frame (Fig. 1.1) affixed to a subject's head (in this case, a monkey), and aligned using external anatomic landmarks, such as the auditory canals and the orbital rims. Using that alignment, the device allowed electrodes to be introduced into the skull and moved to locations within a Cartesian space defined by the frame. Horsley and Clark called their device a stereotaxic frame and brought several ideas to the forefront, notably the use of an external device to define a space within an anatomical structure, and the guidance of a tool or sensor to a point within that space. Horsley and Clark also used serial sections and illustrations derived from the sections to map where they wanted to move their instruments. This idea presaged tomographic imaging by more than 50 years. Horsley and Clark also introduced the concept of a spatial brain atlas. In an atlas, the user assumes that certain structures or functions can be found at particular spatial settings on the frame. The fundamental flaw in their system was that they assumed the monkey brains possessed a constant structure; that is, that one monkey's brain is the same as another. This led them to believe that external structures (auditory canals and orbital rims) could be used to accurately predict the location of internal structures.

To resolve these issues, and for stereotaxy to progress from physiological experiments on monkeys to medical procedures on humans, a methodology for obtaining patient specific information about internal structures

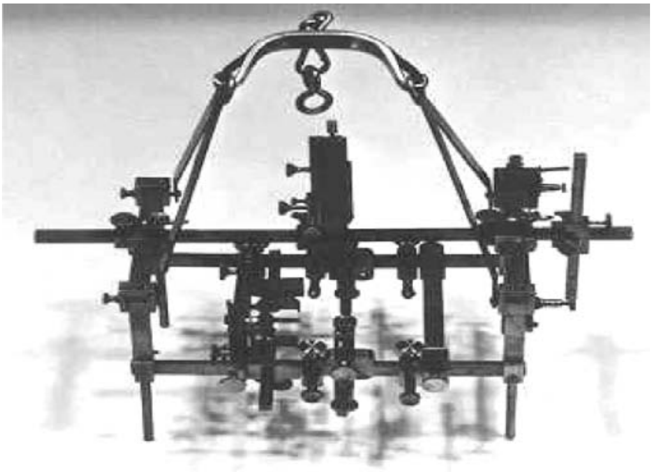

Fig. 1.1. The Horsley–Clarke stereotactic frame

had to be developed. Development of that methodology for the human head would take several decades.

It is curious as to why stereotaxy, and later, image guidance, arose in the field of neurosurgery but not in other therapeutic fields, although there are two probable reasons. The first is that the brain is the only organ encased entirely in bone. This allows the rigid attachment of an external guidance device to the skull, providing a platform for guidance. The second reason is that the brain tissue is largely non-redundant and non-regenerative, so the tissue in the path of the surgical target may be more crucial than the targeted tissue. The advantage of a guidance technology able to limit damage to healthy tissue was sufficient to overcome the usual inertia and resistance toward the adaptation of a new, complex technology.

Further development was hampered by the need for patient-specific information and target localization within the brain. The only realistic way to gather patient-specific information is to image it, and in the early years of medical imaging, plane-film x-ray was the only real choice. Given the high x-ray absorption of the surrounding skull and the relatively subtle changes in x-ray absorption between soft tissues, the soft tissue compartments of the head provided little contrast in a plane-film x-ray, which only displayed differences in the line-integral absorption of the x-ray beams. It was Dandy's [1918, 1919] invention of pneumoencephalography and ventriculography that allowed for some contrast between soft tissue compartments of the brain, providing patient-specific measurements of brain anatomy.

The availability of this imaging capability led Spiegel et al. [1947] to develop the first human stereotactic frame. Their device, while mechanically echoing the Horsley and Clark [1908] frame of almost 40 years earlier, was designed so that two orthogonal images, one anterior-posterior (AP) and the other side-to-side (lateral), could be made. The frame was constructed in such a way that it appeared in the images together with information about the patient's anatomy. Again, the images are projections of interior structures, so finding a three-dimensional point in the anatomy required it being precisely identified in both the AP and lateral images to resolve the third dimension. Although the Spiegel frame opened the door to human stereotaxy, its major weakness was how the frame was attached to the head. They used a plaster cast that swathed the patient's head and held struts attached to the frame. The plaster cast was held to the skin by friction and if the skin moved under the weight of the frame, it changed the relationship between the frame position and the anatomic structures.

Whether inspired by Spiegel and his colleagues or by independent creation, a number of surgeons developed their own stereotactic frames in the late 1940s and early 1950, the details of which can be found in Gildenberg and Tasker [1998] and Galloway [2001]. Four systems, in particular, deserve some additional mention. Tailarach [Talairach 1957; Talairach and Tourneau 1988, 1993] revisited the idea of a spatial atlas. His approach was to assume that all brains were not the same, but varied by a series of proportions. This meant that if certain anatomical structures could be visualized and measured, they could be used as scaling terms to an atlas, thus allowing a general atlas to be "fit" to a specific patient. Such a technique presaged the automatic rigid [Collins et al. 1994] and non-rigid [Collins and Evans 1997] registration methods used for intra-patient comparisons today. In addition, Chapter 6: Rigid Registration, and Chapter 7: Nonrigid Registration, give more detailed descriptions of these topics.

In Germany, Traugott Riechert and Wolff [1951] and later Fritz Mundinger [1982] developed a device that differed from all the preceding frames. This frame dealt with the head, not in a Cartesian format, but in spherical coordinates. This allowed access to structures within the head by moving along the cortical surface. This process also reduced the maximum distance from the frame to the head, thus reducing the effect of inaccurate angular positioning.

Leksell [Leksell 1951; Leksell and Jernberg 1980] also realized the advantage of breaking from Cartesian coordinates, but his system was structured on polar coordinates and introduced the idea of moving the device (a moveable arc mounted on the frame), such that its isocenter could be aligned with the target position (Fig. 1.2). By moving the arc so that the target was always at its center, all probes, electrodes, or other surgical instruments could be the same length. When at their fullest extent, the target was reached. Leksell [1968, 1983] also realized that other forms of therapy, such as radiation treatment, would be enhanced by improved guidance and he later developed the “Gamma Knife” system for radiation delivery (also see Chapter 16: Radiosurgery, for more discussion).

Fig. 1.2. Modern Leksell Frame equipped with isocentric targeting device

Of the stereotactic frames developed in the 1960s, the Todd–Wells [Todd 1967] is notable, not so much for its design, but for the fact that it served as the foundation for a number of other stereotactic systems. These include the Brown–Roberts–Wells (BRW) frame, the Cosman-Roberts–Wells (CRW) frame, and the Compass System.

For most of its history, the role of stereotaxy was to allow the surgeon close access to the target. Most stereotactic cases were for treatment of seizures or movement disorders, and consisted of ablation of erratically firing cells. Since such cells are radiographically indistinguishable from the surrounding healthy tissue, the surgeon had to determine the area of the brain to approach based on physical examination, and then use images to capture patient-specific information to locate the zone. The targeting was then refined by moving an electrode through the area until pathologic electrical signals were detected, or a desired patient response was elicited through stimulation.

In a 1987 article in Neurosurgery entitled, “Whatever Happened to Stereotactic Surgery?” Gildenberg [1987] documented the steep reduction in the number of stereotactic procedures after the introduction of L-Dopa in 1967. This was a good example of a medical treatment supplanting a surgical approach. At the time of writing, it is rather interesting to see the rise in deep brain stimulation, a surgical procedure that deals with the failure in the long-term use of L-Dopa and its pharmacological descendents.

1.3 The Arrival of Computed Tomography

In 1973, Hounsfield and EMI [Hounsfield 1973] announced the invention of the computed tomography (CT) scanner, which allowed the direct acquisition of three-dimensional image information about the internal structures of the brain. With CT, the voxels were highly non-isotropic due to the thickness of the slice (typically 13 mm in 1973). Although Hounsfield and EMI had had a difficult time finding commercial backers for the technology, it was quickly embraced by the diagnostic radiology community [Davis and Pressman 1974]. In the early 1970s, EMI's main activity was the recording and marketing of popular music and it is probable that the success of the Beatles in the 1960s was directly responsible for funding EMI's development of the CT scanner.

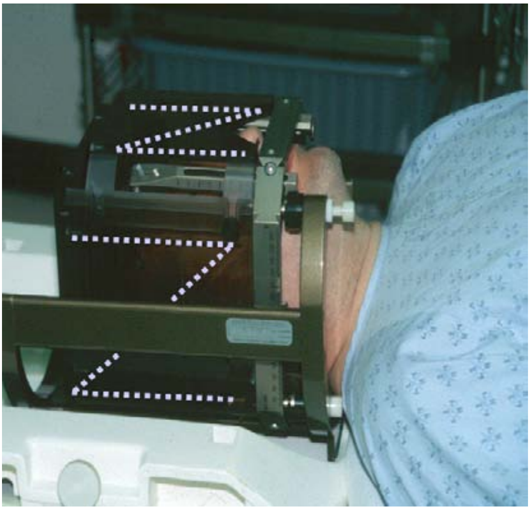

Fig. 1.3. "N"-bar system (embedded in acrylic frame but highlighted as *dashed lines*) attached to a stereotactic frame prior to imaging, as a means of registering the image to the patient

During this period of development, the therapeutic side was not lagging behind. Bergstrom and Greitz [1976] described their early experience of CT using stereotactic frames, and this was followed by many other reports describing the adaptation of CT in stereotactic surgery. In 1979, Brown published a methodology for determining the three-dimensional stereotactic position of any target point visible in a tomographic image. His method required placing radio-opaque bars that formed a letter "N" on the sides and the front of the frame worn by the patient. There were several important consequences of this technology. First, it made each voxel in the image independently addressable in both image space and physical space, removing the need to match target points on two plain-film x-rays. By removing the requirement that a target be unambiguously determined in two images, the choice of targets and therefore the targeting precision increased dramatically. The second consequence of the Brown "N" bar system is that it allowed the integration of the localization system and the registration process (Fig. 1.3). A frame with an N-bar system could serve both as a rigid tool platform and as a means of registration. One clever technique developed by Gildenberg and Kaufman [1982] allowed for the transfer of target points from a CT image into pseudo AP and lateral images, allowing pre- N-bar systems to make use of the new imaging modality.

In spite of the success of CT, the use of radiographs for stereotactic surgery did not entirely disappear. When vascular structures were involved, it was often necessary to use angiography alongside the CT images to ensure vascular-free pathways to the target. When using angiographic images, an alternative fiducial marker configuration comprising two sets of point objects on frame-mounted plates perpendicular to the central rays of lateral and AP x-ray beams were employed [Peters et al. 1994]. This configuration is similar to that described earlier, except that locations of points determined using the angiograms could now be directly related to the three-dimensional coordinate system defined by the CT image volume. Each of these points appears clearly in the projection images, and their positions can be used to precisely determine the imaging geometry. Using this approach, three-dimensional localization of structures within the brain could be achieved using orthogonal (or even stereoscopic) image pairs [Henri et al. 1991a,b] while superimposing them on the appropriate CT image.

Beyond the mechanics of using an old technology with new data, the presence of volumetric imaging allowed surgeons to consider new applications. Led by Kelly, then of the Mayo Clinic [Kall et al. 1985; Kelly 1986], surgeons began to use CT-based stereotaxy for surgeries beyond the classic cell ablations for movement and seizure disorders. Tumor, vascular, and functional surgeries were all facilitated using the information from tomographic images, a process that gained even more momentum with the release of the first magnetic resonance imaging systems in the late 1970s.

1.3.1 Computer Systems Come of Age

One development crucial to image-guided procedures that should not be overlooked is the August 1981 release of the IBM personal computer (PC). Although a number of neurosurgery systems had used computing systems (most notably the work by Shelden et al. [1980]), they required either specialty computer systems or massive amounts of data reduction, usually performed at the console of the tomographic imaging system. One of the first PC-based systems, with capabilities to plan stereotactic procedures from CT, MRI, or digital subtraction angiography (DSA), was that of Peters et al. [1987, 1989]. This increase in computing power triggered one of the most important changes in thinking, which was crucial to the advent of IGI. Prior to CT, for all types of medical images, the message was embedded in the medium. The images were formed on the method of display, for example, photographic film, whether the procedure involved plane-film x-ray, angiograms, or ultrasound. Using CT, the images existed as numbers *first* and then became converted to either film or cathode-ray displays. It should be noted that a large number of small computers existed prior to the IBM PC, but the legitimizing effect that the support of such a prominent company lent to this new technology cannot be ignored.

Stereotaxis can be grossly simplified as a process in which one "locates the target in the images, then moves to the target in physical space." In the mid- to late 1980s, at least four groups realized that the workflow of that process could be reversed. The new idea became to "determine present surgical position and display that position on the images." This made trajectory decisions an active process in the Operating Room ("how do I get from here to my target?"), but it allowed all the image information to be used actively as that decision was made or modified. It also provided multiple landmarks, so that there was no need to designate tumor margins as a surface of targets, or blood vessels as targets to be avoided. Such systems generally dispensed with the frame, performing image-to-patient registration using homologous landmarks instead. Thus the term "frameless stereotaxy" was born.

All the first four systems used tomographic images, a three-dimensional localizer/tracker, and a registration methodology. Initially, all four systems used anatomic landmarks as fiducials, generally the nasion of the nose and the tragi of the ears, so the difference was in the localization systems and in the methodology of display. We identify these four as simultaneous discovery/invention, because it is clear that work was proceeding on all four before the first public disclosure was made. They will be discussed here in the order of publications of first manuscripts.

1.4 Image-Guided Surgery

The first of the "frameless stereotactic" systems came from Roberts' lab at Dartmouth [Friets et al. 1989; Roberts et al. 1986]. They used a spark gap sonic system (there is further discussion on this in Section 1.5.1 of this chapter) affixed to the operating microscope with a single, dynamically updated tomographic image. The second published system was from the group at the Tokyo Police Hospital [Kosugi et al. 1988; Watanabe et al. 1987]. Here, an off-the-shelf articulated arm was used as a localizer, and the display consisted of a scanned sheet of tomographic images. In the 3 years between the first Roberts' paper and the first from the Vanderbilt group [Galloway et al. 1989], there had been a significant increase in the available computing power and display capabilities of small computers. Based on this technology boost, the Vanderbilt group [Galloway et al. 1993; Maciunas et al. 1992] developed an articulated arm designed exclusively for neurosurgery and for simultaneously displaying the surgical position on three dynamically updated orthogonal cut planes. The last of the four pioneering systems was also a custom articulated arm and perpendicular display [Adams et al. 1990a]. This system was noteworthy for two reasons. First, it addressed one of the major problems in articulated arms, which is the weight of the system, by suspending the arm from a fixed stand. The second reason was that this system was proposed for otolaryngology as well as neurosurgical procedures.

From these beginnings, articulated arms of various configurations were developed by research labs [Guthrie and Adler 1992; Koivukangas et al. 1993] and used in early commercial systems. However, articulated arms represented conflicting requirements. To be accurate, the arms could not flex appreciably over their length, requiring short, thick, arm segments. For ease of use, however, the arms needed low mass (and thus low inertia), but the base of the arm had to be mounted well away from the patient. These requirements forced the design of long, slender segments. It was the conflict between these requirements that prompted the development of free-hand localizers.

1.5 Three-Dimensional Localization

Three-dimensional localization can be achieved by means of geometric, triangulation, and inertial guidance. Articulated arms are a subclass of geometric localizers, and determine the position and angulation of the tip by measuring changes in arm angle and/or length from an initial zero point. All articulated arms used to date for surgery have been revolute arms, that is, they have fixed-length arms and they determine position by sensing the angles between the arms. The new (2006) da Vinci “S” surgical robot from Intuitive Surgical Inc. (Sunnyvale, CA), and some of the robotic biopsy work by Cleary et al. [2003] can be seen as the first step toward localizers that sense length change.

Considerable work has been performed on inertial guidance systems in aircraft and ships, and miniaturization of the component parts has made the creation of a handheld device possible. However, even in air and water craft, inertial systems are being supplanted by global positioning systems, a method of triangulation.

If geometric systems have conflicting requirements, and inertial systems are impractical for handheld tracking, the method of choice for localization and tracking must be some form of triangulation. There are two distinct methods of creating a triangulation system: fixed receiver and fixed emitter. In a fixed receiver system, three or more one-dimensional receivers (or two or more two-dimensional receivers) are placed in a known space in a known geometry to define a relative Cartesian space. An emitter placed in that space produces an energy pulse of some type. This pulse propagates to the receivers, and either the distances (generally through a time-of-flight

(TOF) calculation) or the angles between the emitter and the receivers are determined, allowing the location of the emitter to be calculated relative to the sensors. If one wishes to track and localize an object and determine its location and orientation, then three or more emitters must be placed on the object. Although three is the minimum required mathematically, all triangulation measurements contain noise that leads to spatial uncertainty. This uncertainty can be mitigated by placing additional transmitters on the object, converting the solution from a deterministic to a least-squares error minimization with concomitant noise reduction.

The other form of triangulation, fixed emitter, turns the geometry around. For fixed emitter, the tracked object holds the sensor and the transmitter defines the Cartesian space. Because it is easier to make small magnetic or radio frequency receivers than it is to make effective transmitters, most magnetic tracking systems are of the fixed emitter type.

There is one special case of localizer that is a hybrid fixed receiver, fixed emitter. The Beacon System (Calypso Medical Technologies Inc. Seattle, WA) uses a passive, implanted device that receives an energizing radio-frequency pulse and then emits a frequency-shifted response to fixed receivers [Balter et al. 2005]. An array of receivers permits the received signals to be decoded in terms of the position of the transponders.

1.5.1 Handheld Localizers

As was the case with the creation of what we now call image-guided surgery, it is difficult to sort out the beginning of devices that provide freehand localization and tracking. Clearly, three-dimensional localizers other than articulated arms had been available for decades prior to their use in surgery. However, at least three groups in the early 1990s proposed the use of sonic, TOF triangulation systems for tracking surgical tools in neuro-surgery. These three groups were those of Barnett at the Cleveland Clinic [Barnett et al. 1993], Bucholz at St. Louis University [Bucholz and Smith 1993], and Reinhardt et al. [1993] in Basel. In all of these systems, as in the Roberts' tracked microscope, receivers were placed in a fixed geometry at known locations. A source of sound beyond the human audible frequency range is transmitted as a pulse, and the time taken for the sound to reach each of the receivers is measured. The distances between the receivers and the emitters are calculated by measuring the TOF and dividing by the speed of sound. From these distances the emitter location can be determined.

Sonic systems suffer from two major problems, both of which are related to the speed of sound. The first problem is that while the speed of sound at standard temperature and pressure (STP) in air is nominally 330 m/s; humidity and temperature can cause variations sufficient to cause significant localization errors. Speed of sound induced errors can be overcome by using a surfeit of emitters that free the speed of sound from being a single constant, but the second problem limits the number of transmitters.

The second problem is that the receivers must be placed at least a meter from the patient to allow for measurable differences in TOF. This means it takes 3 ms for the pulse to reach the receiver. To prevent confounding echoes being detected as new source firing, the source activations must be spread out by at least 9 ms for a 1 m source/receiver distance. To resolve a three-dimensional device in space and attitude, at least three independent, non-collinear emitters are required. From the argument above, it is clear that more than four would be preferable. Using five as an arbitrary number, then five independent transmissions would be needed, each of 9 ms or 45 ms in total. During that time, the tracked object cannot move. If the receivers are moved further away from the patient, this problem becomes worse. In the case of the Roberts' tracked microscope, the inertia of the microscope prevented rapid motion, mitigating this effect. However, in a handheld tracking system for surgery, such a requirement puts an unreasonable burden on the surgeon to pay attention to the requirements of the tool. If the tool moves when the emitters are firing, then the solution to the equation degenerates and the answer becomes invalid. This was addressed by some developers by inserting a switch, which was to be pressed when the tool had settled into a desired position. While the switch addresses (to some extent) the motion-induced error, the system is no longer a localizer/tracker, but has become merely a localizer.

If the problem with sonic localizers is the speed of sound, then why not use light? Strobe-based, three-dimensional video position tracking had been known for a number of years, and the development in the 1980s of increasingly more efficient infrared light-emitting diodes (IREDs) made lightweight moving emitter configurations possible. There were initially two fundamental approaches, which were supplemented by a third approach that arrived later. The first approach used active IREDs as emitters. This made use of the sensitivity of charge-coupled device (CCD) light sensors sensitivity to near infrared light. By placing a visible light filter in front of the sensor, it became relatively easy to distinguish the IREDs from other light sources in the room. Two distinct systems emerged from this approach: the Optotrak 3020 (Northern Digital Inc, Waterloo, ON, Canada) [Maciunas et al. 1992; Zamorano et al. 1994] and the Flashpoint 3D localizer and Dynamic Reference Frame head tracker (Pixsys, Boulder, Colorado) [Tebo et al. 1996]. Both systems were adapted into surgical guidance systems. To address the price disparity between the Optotrak 3020 and the Flashpoint, Northern Digital developed a smaller system known as the Polaris, which has become the most commonly used localizer in image-guided systems.

The second optical approach was the direct offspring of video techniques used in biomechanics, automotive destructive testing, and other active deformation applications. Here the target was a passive reflector, often a pattern of lines and bars that can be extracted from two video images. In some ways this is a throwback to stereotactic frames and the need to locate points in AP and lateral x-rays; however, there is greater control in target geometry. One of the most successful approaches was the VISLAN project [Thomas et al. 1996; Colchester et al. 1996] from Guy's Hospital. A slightly different approach came from Brigham and Women's' Hospital, where a single camera was used, but a laser stripe was passed over the object [Grimson et al. 1998]. This technique cannot provide real-time tracking, but has found new applications in shape identification using laser range scanners [Sinha et al. 2005].

The major advantage of reflective systems is the low cost of the "emitter." These are merely reflective structures that can be as simple as patterns printed on a laser printer [Balanchandran et al. 2006]. The major problem with visible-light reflective techniques is that ambient light can confound the system. In an attempt to retain the advantages of passive systems, but to mitigate this weakness, Northern Digital developed a version of the Polaris that used infrared reflective balls mounted on their tracked probes [Wiles et al. 2004]. Such a technique retains the wireless nature and light weight of reflective systems, but filters the reflected light to allow clear identification of the reflectors.

All optical systems, whether active or passive, require that a line-of-sight be maintained between the emitter and the receiver. In some applications, such as when a flexible tool is desired, optical techniques are not optimal. A number of researchers, beginning with Manwaring et al. [1994], have used electromagnetic systems (See footnote in Chapter 2 Tracking Devices, page 26) for their tracking. The major advantage of these fixed-emitter systems is that as the EM signal can pass through the body, the sensor can be placed on the tip of the tool that enters the body. This spares the device from the errors caused by calculating the tool tip from the device trajectory, and allows the tool to be as flexible as desired. The use of flexible tools opens the way for tomogram-guided interventional radiology [Banovac et al. 2002]. Electromagnetic tracking has not yet attained the accuracy of optical tracking, and the presence of large metal structures in medical procedures and operating rooms can cause significant localization errors [Birkfellner et al. 1998a,b]. Chapter 2 discusses tracking in more detail.

1.6 Registration Techniques

The development of tomographic image sets providing three-dimensional information about the patient anatomy, location, and extent of disease, and the advent of three-dimensional spatial localizer/trackers has prompted the development of techniques to determine the relationship between these distinct spaces. This process is known as registration. When the mathematical relationship between a point in one space and the homologous point in another space is known, the spaces are considered registered. If that relationship can be reduced to a single common translation and rotation, the registration is considered rigid. In the field of stereotaxy, as the frame was visible in the image, registration was automatic. Once the frames were removed with the rise of image-guided surgery, then techniques had to be developed to map one space to another.

The obvious method to register these spaces was to identify homologous points in both the image space and the physical space. Use of these intrinsic points coupled with least square error transformation techniques, such as that of Arun et al. [1987] or Horn [1987], allows for the rapid registration of spaces. However, there are two problems with such methods. The first is that distinct points on the human body are not easily identified. Most shapes are rounded and it is difficult to pick out points either in image space or in physical space. The second problem is that the spatial uncertainty in a tomographic image in the thickness of the slice makes it impossible to determine precisely where the point lies within the slice.

Given the dearth of good intrinsic points to serve as reference points or fiducials, researchers have tried placing extrinsic objects with desirable characteristics on the patient for use in registration. These fiducial markers have been designed to stick to the skin [Zinreich et al. 1994] or be implanted into the bone [Maurer et al. 1997]. Because the markers were of a known size and geometry, and were designed to appear in more than one image slice, the spatial uncertainty of localization was greatly reduced. The mathematics of marker registration and marker design are discussed in detail in Fitzpatrick and Galloway [2001].

The field of registration has been dominated by the techniques of image-to-image registration, whether across modalities for the same patient, time series for the same patient, or across subjects for the creation of image atlases. In image-to-image registration, point-based registration has the advantage of having the most easily quantified outcomes, but for the reasons discussed above, the need for prospective placement of fiducial markers limits the usefulness of point-based techniques. Retrospective techniques that do not rely on point identification are clearly preferable, given a few qualifications. One of the first techniques was from Pelizzari et al. [1989] where surfaces were extracted from image sets and fitted together like a hat on a head. The greatest advantage of the surface registration was its ability to be used retrospectively; the greatest disadvantage was that it was difficult to quantify the quality of the registration.

In a landmark paper by West et al. [1997], a controlled experiment of image-to-image registration techniques was performed. Image sets with hidden point-based information were made available to researchers in the field, so they could use their own techniques for registration of the image sets. After they were satisfied with the registration their algorithms created, the hidden information was unveiled and the registration quality was then quantified. This study showed that point-based and volume-based [Hill et al. 1994] image-to-image registration techniques performed significantly better than surface-based registrations, after which the surface-based techniques fell rather into disfavor.

IGI requires image-to-physical space registration, and volumetric techniques are impractical, if not impossible. This has led to a slow reappearance of surface-based techniques for image space to physical registration. The problem of quantification of the registration quality remains, although there are glimmers of new techniques that allow the determination of which surfaces will provide good surface registration [Benincasa et al. 2006].

Physical space surfaces can be obtained by tracked intraoperative imaging such as ultrasound [Lavallee et al. 2004] by moving a tracked probe over a surface, or by the use of a laser range scanner [Herring et al. 1998]. The physical space surface is generally a cloud of three space points, which then can be matched to an extracted surface from image space via a number of iterative mathematical approaches. Most of the mathematical approaches are related to the iterative closest point algorithm developed by Besl and McKay [1992]. Further details on registration can be found in Chapter 6: Rigid Registration, and Chapter 7: Nonrigid Registration.

1.7 Display

The last component of early IGI systems is the display of surgical position and trajectory. The display task is often overlooked as being less important than the localizer or registration step, but it is the step where the data can most easily be misrepresented.

With the advent of modern tomography, good localizers, and functioning registration methodologies, the IGI task is inherently at least a four-dimensional task (three spatial dimensions plus time). Yet, even the most modern of displays can only display two spatial dimensions at once and even holographic displays only display the surfaces of the objects that were imaged with the hologram. So the challenge is to display four dimensions (three space + time) of information on a three-dimensional (two space + time) display. In addition, such a display must be as intuitive as possible, so the surgeon does not spend time and effort understanding the display instead of considering the surgery.

As discussed earlier, the four-quadrant, cardinal plane display common to most guidance systems was independently invented by Galloway et al. [1993] and Adams et al. [1990]. By presenting slices in standard orientations with perpendicular information, such displays allow for the transmission of multidimensional information in a relatively easy-to-grasp presentation. However, at any given point in time, the presented information is only the slices congruent with the estimated surgical position. If the surgeon wishes to consider moving obliquely to those planes, the anatomy to be traversed by such a move is not shown on the display.

In the 1990s, a new class of computer called a workstation began to become available to IGI system designers. One of the principles discerning features of workstations compared with other computers was the concern with the graphical performance of the machine. Workstations typically provide a great ability to perform sophisticated rendering and other graphics functions. Developers began to consider image pixels as textures that could be applied to shapes, allowing for display of transverse, sagittal, and coronal information on the same rendering [Barillot et al. 1991]. However, those systems still were hampered by the dimensional problem of the display. What surgeons needed to see was not their location, but the structures that were immediately beneath their location.

A group at Brigham and Women's Hospital attempted to address this problem with a methodology they called "enhanced reality" [Grimson et al. 1996]. Here, the tomographic data was reduced to important structures, such as the tumor and nearby blood vessels. These structures were then rendered and mixed into a perspective display according to the surgeon's viewpoint. By placing internal objects within such a display, the aim was to display the head as being transparent, allowing the surgeon to understand the location and orientation of internal structures.

One of the challenges of designers of IGI systems in dealing with three-dimensional data is that the human visual system is really only 2.5 dimensional in space. Binocular vision allows a viewer to understand the relative position of structures, but not to see within. The Montreal Neurological Institute has a long history [Henri et al. 1990; Peters et al. 1990a,b] of obtaining stereo pair angiograms that allow the viewer to determine the relative positions of vessels and vascular abnormalities. Angiograms do this well, because only by visualizing the vessels can you reduce the information density. There is no pressing reason to see inside the vessel for the guidance of therapy.

In addition, to accomplish true binocular vision, there must be an image presented to the right eye, and a distinct image presented to the left eye. If either eye perceives the image presented to the other, the binocular effect is lost. The need for complete separation has led to the development of various forms of head-up displays. Clearly, the operating microscope is a logical place for insertion of data; however, inserting information into the visual stream without disturbing the light microscopy function presents some challenges to the designers [Edwards et al. 1995]. Other designers do not employ the microscope at all [Birkfellner et al. 2000], but use small monitors to display information separately to each eye. Surgeon acceptance remains a challenge for this approach.

1.8 The Next Generation of Systems

Currently, what are the remaining challenges? Although advancements have been made in imaging, localizers, registration, and display, no one can claim that the ideal has been found for any of them. In addition, one of the fundamental concepts of the whole field, which is that the images represent the present state of the physiology, is only a first approximation. Attempts to address this by decreasing the time between image and intervention led to the development of intraoperative tomography [Fichtinger et al. 2005]. However, there has not been a significant advancement in medical outcomes to justify the cost and complexity of such systems. Research is ongoing to see if the cost and complexity can be reduced.

A separate approach is to attempt to understand and model the deformations that occur both peri-procedurally and intra-procedurally. Again, the ongoing march of performance to price of computers is allowing for large, mathematically sophisticated models [Cash et al. 2005; Paulsen et al. 1999; Warfield et al. 2005] to calculate solutions in surgically appropriate time scales.

We are rapidly closing in on the twentieth anniversary of what is now called IGI, with new applications being developed almost monthly. A whole generation of neurosurgeons has completed their residencies, culminating in an expectation that operating rooms will come readily equipped with image guidance systems. It is a tribute to the designers that their systems have become commoditized, but acceptance should not breed complacency. As evidenced by the rest of this book, there is exciting work still to be done and problems yet to be solved.

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