The Future of Stereotactic and Functional Neurosurgery

188 The Future of Computers and Imaging

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Historical Perspectives

Computer and imaging technologies have had a major impact on the field of stereotactic neurosurgery in the last 30 years. The first known human stereotactic procedure was performed by Spiegel and Wycis in 1947 using manually calculated methods of determining a target for coagulating the dorsal median nucleus of the thalamus [1]. Through the 1960s, many centers performed human stereotactic procedures primarily for the treatment of movement disorders and chronic pain using manual calculations. The advent of L-dopa in 1968 caused a dramatic decrease in stereotactic procedures until the development of computed tomography (CT) in 1971.

CT ushered in the era of image-guided stereotactic procedures. The first production class CT scanner, known as the *EMI-scanner*, acquired two adjacent slices in about 4 min and then was postprocessed on a Data General Nova minicomputer in another 7 min into 80 pixel by 80 pixel slices. Each new generation of CT scanner generated higher resolution three-dimensional images over a larger field of view in a much shorter amount of time.

With the advent of CT, a small number of centers began developing computer software and systems to automate manual calculations and to perform more sophisticated image-guided interventions. Our group began using a Data General mini-computer attached to a Tektronix vector display and a sonic digitizer in order to calculate coordinate target points and transpose image-derived volumes on a modified CT-compatible Todd-Wells stereotactic frame in the late 1970s at the Erie County Medical Center in Buffalo, New York [2]. The Data General S140 computer, configured with a mere 128 kilobytes of memory was the size of a large refrigerator. The nine platter 192 megabyte (MB) external disk drive was the size of a washing machine. An Apple II personal computer was used as a remote display in the operating room to perform the first CT-based, computer-assisted laser resections of deep-seated brain tumors [3–5]. This whole computer configuration cost about $100,000. Our group later moved to Sisters of Charity Hospital in Buffalo and incorporated another Data General minicomputer-based system: an Independent Physician Diagnostic Console (IPDC, General Electric Medical Systems, New Berlin, Wisconsin). This system contained a 320 × 320 raster display device which allowed us to develop software to directly display and manipulate CT, MR and digital angiographic images and write software for the simulation and performance of a variety of image-guided stereotactic procedures including biopsy, thalamotomy, interstitial implants and volumetric craniotomies [3–13]. Your cell phone has more computing power and storage than either of the computer systems our group started with years ago.

Computing Perspectives

Gordon Moore, a founder of computer chip manufacturer Intel, predicted in 1965 that the number of transistors on integrated circuits would double nearly every year, thereby approximately doubling the speed, memory access and capacity comparably in the same timeframe [14]. Processors and memory technology have generally followed this prediction. Engineering-class and personal computers used in image-guided surgery systems have traditionally contained a single central processing unit (CPU) connected to internal random access memory (RAM) and external, but slower data storage on external (hard drive) peripherals. The focus had been on making single CPUs process data even faster by making larger and more capable processor chips on a single silicon wafer referred to as *wafer scale integration*.

Highend, "supercomputers" have, for years, integrated multiple processors within the same system. This technology has recently trickled down to advanced engineering workstations and personal computing systems over the last few years. These systems are defined by separate, but interconnected, processor chips contained on a single integrated circuit board. More recently, multiple *core* processors are making their way into commodity-type personal computers. Multiple core systems package multiple processors into a single component on an integrated circuit board. Both of these multiprocessing technologies attempt to speed up computer calculations by techniques known as pipelining and multithreading.

Software does not automatically execute linearly or exponentially faster using multiple processor or multi-core systems. For example, a software program will unlikely execute two times faster on a two-processor or two-core computer. The software has to be separated into pieces that can be efficiently executed in parallel on the multiple processors and this is not a simple task [15]. Amdahl's Law for processor speedup postulates that the theoretical maximum performance increase using parallel computing versus single CPU computing would be about twenty times no matter how many processors/cores are used if 95% of a program can be parallelized [16]. Therefore, at the current time, it appears like there is a theoretical limit on the numbers of processors/cores that can be utilized to optimize the speed of an algorithm even through there is no current hardware limit on the number of processors/cores that can be built assuming you could provide the power and dissipate the heat generated by such systems. Furthermore, software engineering tools for developing, optimizing and debugging multi-processor software are a generation behind hardware developments, but the benefit of general purpose multiprocessing technology is huge.

Increasing individual processors calculation speeds and combining these processors into multiple processors and core systems is not the only way to increase computer performance. Bottlenecks in the communication between processors slow down the overall benefit of multiprocessor systems. Current technology uses small wires to facilitate communication between processors and there is a fundamental limit in the speed by which data can move over wire technology. Additionally, wire technology utilizes extra electrical current and worst of all, generates heat that must be dissipated.

Novel research is currently underway to develop new technologies to increase the computational speed while decreasing the electrical current and the production of heat in multiprocessor computer systems. *Silicon Photonics* is a evolving field within computer science to provide a more efficient manner to interconnect chips at high speeds so that newly developed computer systems are perhaps a thousand times faster, more energy efficient and produce less heat. Sun Microsystems has recently been awarded a multiyear grant from the Pentagon to explore options for replacing wires used to communicate between chips with laser technology. Each chip would interconnect and communicate at extremely high speeds with every other chip using laser light that could carry tens of billions of bits of information every second. NEC, a Japanese maker of supercomputers also recently announced advances in optical chip interconnections for supercomputers that too, will trickle down into the engineering and personal computer technology used in image guided surgery.

Imaging Perspectives

Advances in medical imaging have come a long way since the early days of image-guided surgery. The typical first-generation image-guided dataset was a relatively small number (10–30 slices) of rather thick (5–10 mm) preoperatively collected 256 × 256 or 320 × 320 pixel computed tomography (CT) images. Digital angiographic and MRI images were integrated into the image-guided repertoire in the early 1980s as soon as hardware registration methods and image transfer software were developed. One center incorporated a CT scanner directly in an operating room in the early 1980s [17]. New imaging modalities as well as other digital input sources of data will continue to be integrated into image-guided databases.

Currently the majority of image-guided procedures use one, or perhaps two, preoperatively collected imaging databases such as computed tomography (CT) or variations of images collected from magnetic resonance (MR) scanners. Some image-guided procedures are now being performed in an operating room adjacent to a scanner and the patient moved back and forth when an updated scan may be necessary. Other systems are available to move a scanning device to the patient such as a track-mounted MR or a mobile C-arm system that creates near-computed tomographic images intraoperatively. Many of these portable systems are bulky or hard to move around, may be limited to being used in only one operating room or do not fit well in a relatively smaller sized operating room that is available at many institutions. Some centers are performing procedures within the imaging unit, but not all image-guided procedures are candidates for being performed in the confines of the scanner.

A variety of advances in imaging technology are discussed elsewhere in this textbook. From a technical perspective, advances in imaging technology will impact image-guided surgery by delivering a wider variety of more densely collected datasets. Four-dimensional imaging will be the norm in the future. This higher variety and density of imaging data will require more capable computing systems to manipulate these data, many of which will be produced and registered to the patient during the procedure.

Medical image registration and registration of images to treatment delivery systems by sensor based and robotic technologies are described elsewhere in this textbook. Briefly, images are created in a coordinate system defined by the scanning device. Treatment delivery devices generally define their own coordinate system by incorporation of stereotactic headframes, articulated arms, magnetic field and optical digitizers and Cartesian or other robotic devices. Image-guided registration involves spatially relating the imaging data to the treatment device. If more than one image dataset is utilized for a procedure or intervention, they must be individually registered to the patient [18] or correlated or fused to each other and then registered to the patient using image correlation or image fusion techniques [19].

New methods of image to patient spatial registration will need to be developed so that, rapidly scanned, densely collected, intraoperative datasets may be rapidly and accurately integrated and registered into the system. These methods will need to be less obtrusive than current ones, spatially correct for patient repositioning and movement between acquisitions as well as correct for potential geometric distortions inherent to the imaging unit and work even while a patient is underneath surgical drapes.

Tying It All Together

First-generation image-guided systems were developed mainly at academic institutions and combined high performance minicomputers or engineering workstations with stereotactic frames, custom-built Cartesian robotic technology [20] and commercially available articulated arms. Second generation image-guided systems integrated newer sensor technology including magnetic field and optical technology and more sophisticated software. Current generation image-guided systems combine high end personal computers and similar second-generation sensor technology that are often contained in a large cart that needs to be moved into and out of the operating room. A few image-guided systems involve fixed or ceiling mounted systems that work in one or two operating or procedure rooms. Some institutions and manufacturers have focused on developing instrumentation and software to perform procedures directly in an imaging device while others have focused on developing technology to temporarily move the imaging device into and out of the surgical field. Other centers have built operating facilities adjacent to the imaging device allowing the patient to be moved in and out of the scanner when updated imaging is required.

The primary deliverable of an image-guided system is to three-dimensionally direct instruments or guide treatment to specific locations as defined by imaging databases. Imaging data needs to be spatially registered to the patient as positioned during the procedure regardless of the system or method of treatment delivery. Registration is accomplished by a number of current methods that include stereotactic frames, external stick-on and implantable fiducials and surface matching. Frames are considered cumbersome and patients don't necessarily like them, but they do produce the most accurate, reliable and most reproducible accuracy, because they are rigidly attached to the patient and their imaging reference system deposits geometrically well-defined markings on every image leading to a very direct and intuitive spatial mapping between the entire image volume and the delivery mechanism. External stick-on markers are widely used in image-guided surgery, but can move on the skin or even fall off. Externalized implantable fiducials have been available for number years, but these require a minor surgical procedure to implant them and there are potential issues of infection. Both of these forms of external point-based registration techniques involve depositing only a small number of markings in the imaging data to spatially register the images to the delivery system using point matching/least-squares fit registration algorithms. The limited number of external points utilized in these registration methods are not the most optimal, especially when used with potentially geometrically distorted image data that may be provided by, for example, magnetic resonance imaging [21]. Surface registration methods have been available for years, but are not widely used and have limited use when the patient "surface" is hidden under surgical drapes.

Newer image registration methods will be developed that are easy to use, comfortable for the patient, enable highly accurate spatial registration even with potentially distorted imaging data, are less obtrusive and are accessible even under surgical drapes. Wireless radio frequency identification tags (RFID) are being widely adopted to monitor the location of inventory in stores. It is very likely that very small, wireless, multimodality compatible fiducials will be integrated with newer intraoperative sensor and robotic technology in future generations of image-guided systems. Telepresence technology will also continue to be incorporated in image-guided systems.

Computing devices will becoming smaller, faster and contain much more capacity to store and manipulate larger and denser imaging datasets. Newer software methods will also be refined to automatically divide image-guided software algorithms into internal computing code that can take advantage of multiprocessors systems without the software engineer having to worry about how to separate their code into separate segments that can be processed in parallel.

The days of the large, portable equipment rack with a large, optical sensing bar, cables sometime strung across the floor with a monitor 10 feet or more away from the surgeon will be a thing of the past. Computer and imaging systems integrated into current generation image-guided system sits idle during even much of the procedure. Many of these types of systems may remain powered on in an adjacent room waiting for data to arrive from radiology which is not very energy efficient. Furthermore, the average lifetime of the hardware in an image-guided computer and imaging system is generally out of date in a 3–5 year timeframe necessitating large expenditures for the "next generation" of an image-guided system every few years.

Computing power will be delivered similar to how electricity is delivered from an electric utility: you only use what you need and you do not need to provide and support (or buy) your own dedicated system. This type of utility computing is commonly referred to as *cloud computing*. Future image-guided system will utilize cloud computing and will also likely incorporate display technology similar to interactive internet browser-like technology which will only require a small wireless touch screen interface. Speech and voice recognition technology will also be more fully integrated into these types of systems.

The image-guided facility of the future, whether in an operating room or in an imaging scanning facility will be configured as an indoor global positioning system-like (GPS) system [22,23]. An indoor, high fidelity GPS systems will define the work envelop as the entire room eliminating line-of sight or other second-generation sensor-based limitations enabling the patient, wireless registration fiducials, every instrument and the location and directional view of the surgeon to be tracked. The system will automatically incorporate and register intraoperatively collected, dense imaging data, provide the surgeon various methods to view and interact with the imaging data superimposed on the surgical field while optimally enabling them to simulate and deliver instruments or treatments with much higher magnitudes of accuracy than present systems.

Computing and medical image technology have had a significant impact over the past 30 years and will continue to positively impact the field of image-guided surgery well into the future.

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