Image-guided surgery and the spine: a critical review
Cirurgia vertebral guiada por imagem: uma revisão crítica

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ABSTRACT
Computer image-guidance has become more widespread in recent years. Initially, stereotactic principles for cranial surgery were employed for “frameless” cranial stereotaxis. The use of computer-rendered anatomy as a frame of reference has facilitated the use of computer image-guidance outside of the head, particularly in the spine. A number of different computer-image-guidance strategies are now employed in spinal surgery. How effective, useful and accurate these techniques are is the subject of this review. Based on our experience and a review of the published literature, we assess the advantages and possible pitfalls of image-guidance in surgery of the spine. Image-guidance can use pre-operative CT data, intra-operative fluoroscopy or CT or hybrid technology (iso-centric fluoroscopy). Subjective and objective studies are compared with regard to methodology and endpoints. Specific applications at various spinal levels and for a variety of pathologies are reviewed and illustrated. The integration of newer technology including the use of an impedance-sensitive drilling tool is discussed. Compared to cranial image-guidance studies, the possibility of intersegmental movement of the spine has led to some concerns regarding accuracy and to strategies of registration of individual spinal levels. Recent studies indicate that accuracy may be reasonable in some circumstances without separate segmental registrations. Endpoint assessments in cadaver and clinical studies usually look at final position of instrumentation to assess accuracy. Overall, the literature and our experience seem to support benefit from image-guidance as applied to surgery of the spine. Use of the impedance-sensitive drilling tool has provided additional benefit in optimising instrumentation both in our hands and in a multicentre study. Tumours of the spine have also been a useful area of application of image-guidance. Overall, image-guidance in spinal surgery seems to be beneficial, especially in more complex cases. For pedicle screw placement, we found the combination of image-guidance with an impedance-sensitive drilling tool particularly reliable.

KEYWORDS: Spine/surgery; Surgery computer-assisted; Accuracy

RESUMO
Os protocolos dos métodos de imagem têm sido muito divulgados nos últimos anos. Inicialmente, eram utilizados princípios estereotáticos para as cirurgias. Com o advento do uso da imagem anatômica criada pelo computador, conforme modelo tridimensional foi facilitado seu uso na leitura dos dispositivos de imagem, particularmente da coluna vertebral. Diferentes protocolos de imagem são agora empregados na cirurgia da coluna vertebral. De modo efetivo, o uso e a acurácia dessas técnicas são estudados nesta revisão. Baseados em nossa experiência e na revisão publicada na literatura médica, avaliamos as vantagens e os possíveis artefatos da cirurgia da coluna guiada por imagem. O uso da imagem como guia pode ser aplicado na fase pré-operatória, com a tomografia computadorizada (TC), na fase intra-operatória com a fluoroscopia, ou TC, ou tecnologia híbrida. Estudos subjetivos e objetivos são comparados com a observação das metodologias empregadas e seus respectivos resultados. Aplicações específicas e variados níveis espinhais e doenças são revisadas e ilustradas. Também é discutido o treino do recurso da moderna tecnologia que inclui o uso impedância-sensitiva. Estudos comparativos sobre métodos de imagem do crânio, as possibilidades do movimento dos segmentos da coluna têm gerado vários interesses relativos à exatidão e às estratégias de registro individual dos níveis espinhais. Recentes estudos indicam que a exatidão pode ser cabível em algumas circunstâncias sem o abandono dos registros dos segmentos. Assim, o estudo do método em cadáver e em ensaios clínicos mostra a exatidão do posicionamento final do instrumento. Por fim, a literatura e a nossa experiência demonstram a importância dos métodos de imagem guiada como aplicação exata na cirurgia da coluna vertebral. O treinamento do uso da impedância-sensitiva tem fornecido benefícios adicionais em nossas mãos e em estudos multicêncrinos. A aplicação da imagem guiada também tem sido usada nos casos dos tumores espinhais. As cirurgias de coluna guiadas por imagem têm se mostrado eficazes, especialmente nos casos mais complexos. Nos casos da localização dos parafusos pediculares consideramos a imagem associada à impedância-sensitiva particularmente confiável.

DESCRITORES: Coluna vertebral/cirurgia; Cirurgia assistida por computador; Acurácia
BACKGROUND

The exponential development of computer power has had major repercussions not only on medical imaging, but also utilising this imaging information for surgical guidance. Originally, in cranial surgery, frame-based stereotaxis used a frame attached to the skull to define space within a Cartesian frame of reference. Initially, surgical space was related to atlas coordinates but with CT and MRI imaging, frame coordinates could be identified on imaging and the corresponding surgical space (predicated on the frame still being attached to the skull)3. With further increase of computer power, it was possible to render the 3D anatomy of the head on images and then correlate this 3D model with the patient’s anatomy at the time of surgery. This correlation is possible by defining space with regard to a referencing system, now most commonly an optical system in which a pair of cameras detect defined markers and correlate the patient’s anatomy with the imaging anatomy by means of a probe which is also tracked by the cameras (Figure 1-2). Once the creation of a 3D rendered radiological model could be correlated to surgical anatomy, the concept of “frameless stereotaxis” was born. With surface anatomy used as a frame of reference, stereotactic principles could be applied to other surgical targets including the spine.

Image-guided surgery

Image-guidance in surgery has become an interactive means of using a surgical pointer or tool at surgery and visualizing a corresponding virtual tool on images on a computer workstation in the operating theatre. Thus image-guidance systems are used for navigation during surgery by displaying the probe’s location in relation to the images on the computer workstation. In spinal surgery, there have been two main applications of image-guidance:

1) The visualization of trajectories in order to optimise placement of instrumentation, in particular of screws (pedicle screws, lateral mass screws, trans-articular screws, odontoid screws, cervical plate screws etc.)

2) Orientation with regard to difficult tumours involving the spine.

In spinal surgery, the imaging data sets used for image-guidance have evolved in an application-specific manner. The following image data sets have been used for navigation during spinal surgery:

1) Pre-operatively acquired volumetric CT.

2) Intra-operatively acquired digitised bi-planar fluoroscopy.

3) Intra-operatively acquired dynamic iso-centric fluoroscopy.

4) Intra-operatively acquired CT.

5) MRI is rarely used for spinal surgery except for tumours, in which case the imaging is usually correlated to a CT data set.

Referencing of stereotactic space

In order to correlate the position of a surgical instrument or probe with its position on images of the navigational workstation, space needs to be defined as does the position of the probe. The first systems in cranial surgery utilised a triangulation principle using ultrasonic emission and subsequently arm-based digitised mechanical arms were introduced. These systems were cumbersome in their application to spinal surgery. Subsequent triangulation techniques using active or passive optical tracking made application to the spine reasonable. With optical systems, an array of cameras detects active (light emitting diodes; LEDs) or passive (reflective) markers on a probe or instrument, thus tracking the instrument in space (Figure 1). If the patient and the cameras do not move, the probe alone can be used to define space, as some surgeons have demonstrated. If there is movement of the cameras or the patient, however, an array of additional markers must be firmly attached to the patient’s anatomy (i.e. a spinous process) for the computer to compensate for this movement. (Figure 2) This is termed “dynamic referencing” and is the most commonly employed strategy of currently available image-guidance systems. An alternative to optical referencing is electro-magnetic field referencing in which surgical space is defined by generating a magnetic field and detecting the position of a probe (equipped with a magnetic receiver) within that field. Systems using this principle are also commercially available. In cranial surgery, the accuracy of magnetic referencing appears to be similar to that of optical referencing. There are no comparable studies in the spine.
Registration
The process by which the anatomy in “image-space” (on the workstation) is correlated with “surgical-space” (the patient) is known as registration. Registration is predicated on the assumption that the “solid body” in “image-space” remains a proportionate non-distorted “solid body” in “surgical-space”. In order for this principle to hold true in the spine, spinal segments must be relatively immobile with regard to each other from the time of imaging to the time of surgery, or each segment needs to be individually registered. One way of minimizing movement is to acquire images in the operating suite in surgical position. Since it is rare for centres to have intra-operative CT, systems have been developed to import multiple fluoroscopic images into the computer workstation and then use these digitised pictures for multi-planar “virtual” fluoroscopic guidance.

When utilising pre-operatively acquired CT data sets (usually in the supine position), change in intersegmental relationships by the time of surgery (usually in the prone position) may be major (cervical spine), minor (thoracic spine), or intermediate (lumbo-sacral spine). Some recent clinical studies have claimed good accuracy of screw placement with single multi-level registrations in the lumbar and cervical as well as thoracic spine. As discussed above, registration in the spine has the disadvantage of possible intersegmental movement. The advantage in spine is that registration is on bone, which is a more reliable surface than skin for registration.

Registrations at single or multiple levels can be performed using a paired-point, a surface-matching or a hybrid paradigm. (Figures 3-4) In a paired point strategy, a minimum of 3 non-collinear points are selected on the imaging model and then matched to the corresponding points on the patient’s anatomy by way of the tracked probe. The image-guidance workstation then uses a matrix transformation to match the rest of the imaging anatomy to the surgical anatomy. The accuracy of this registration is dependant on how well the points are chosen on the images and at surgery. A surface matching paradigm involves touching a minimal number (usually at least 20) of non pre-defined points of surface anatomy with the probe. (Figure 5) The computer then uses a matrix to match surface contours. There are also systems that use a combination of set points and surfaces. In all forms of image-guiance, the quality of the actual patient-to-image registration at the time of surgery has a major bearing on the subsequent accuracy of navigation. When virtual fluoroscopy techniques are used, as subsequently further discussed, the registration is performed automatically at the time of image acquisition at surgery. (Figures 6-7) Overall, it remains essential for a surgeon to gain insight into and experience with the registration process. Finally, it must be underscored, as with all technology, that image-guidance is a tool to supplement, not replace knowledge of surgical anatomy. Surgeons must always be wary of possible image-guidance “failures” or inaccuracies and be able to over-ride the navigational system based on anatomical knowledge, rather than being too dependant on the technology.

Lessons Regarding Accuracy in Image-Guidance
The accuracy of an image-guidance system is often presented as being in the sub-millimetre range by companies that commercialise the various systems. Whereas this may or may not be true in a laboratory setting, it is certainly not true in a clinical setting. Discussing accuracy requires the definition of a number of terms and concepts;

“Calculated accuracy”
This is a number given in millimetres by the computer after registration has been performed. It is actually the root mean square (RMS) of the error after matrix transformation between the points in “image-space” and “surgical-space”. In other words, it is the computer’s estimate regarding how well it has mathematically transformed corresponding points. This may or may not be a reflection of reality (i.e. the transformation of a cylinder from image to real space may have wonderful calculated accuracy and yet the cylinder could be back to front). A number of studies have suggested that calculated accuracy correlates poorly with true measured accuracy.

“Application accuracy”:
This is a term used to indicate the true global accuracy of an image-guidance system as measured by overall localisation errors of surgical targets.

“Application accuracy endpoint assessment”:
Defining how “accuracy” is determined is a crucial aspect of understanding the literature or designing a study. For many cranial studies, accuracy is reported in a laboratory environment using phantom models in which the localisation errors of designated targets are measured. There are far fewer clinical studies and many of these are biased by attempting to measure localisation errors of unreliable targets. With well defined targets, localisation error in cranial surgery is probably in the 4.0 +/- 2mm range. In spinal surgery, endpoint assessment is different. Phantom studies are replaced by “cadaver” studies and clinical studies are based on follow-up CT imaging. The endpoint for accuracy in both cadaver and clinical studies is the accurate placement of screws in a pedicle, lateral mass or other bony component of the spine. Measures of accuracy are the “non-violation” of cortical bone on cadavers or post-operative imaging. (Figure 8) Although this is a qualitative assessment of accuracy, it assesses the accuracy that is clinically relevant and useful in spinal surgery.

Accuracy in Spinal Image-guidance
In recent years, there have been numerous publications on the accuracy and the utility of image-guidance in the spine. Cadaver studies have compared traditional fluoroscopy with image-guidance based on pre-operatively acquired CT and registered at single levels or multiple levels. Similar clinical studies use post-operative CT to assess optimal placement of screws without and with image-guidance. Virtual fluoroscopy techniques have been assessed in a similar manner and there are also preliminary data on iso-centric fluoroscopy. By and large, all of these reports have found some advantage of image-guidance (in the form of more consistent screw placement with less cortical violation), especially when the target size is technically challenging (thoracic pedicles) or the anatomy is distorted (spinal deformities & tumours).
Applications: instrumentation

As previously mentioned, the most common application of image-guidance in spinal surgery is to determine trajectories for the placement of screws when instrumenting the spine. As such, computer guidance has become an adjunct to the use of anatomical landmarks or has been used to replace anatomical landmarks in the case of percutaneous techniques which are the most dependant on image-guidance. Practical uses of image-guidance in the spine is best reviewed on a level-by-level application-specific basis.

Cervical spine: posterior approaches

Image-guidance can be used for a variety of posterior cervical approaches. For high cervical stabilisation, image-guidance can be particularly useful. Transarticular screw placement at C12 precludes individual vertebral registration since 2 levels are targeted. If C12 is relatively undisplaced, 2-level registration can provide good results. (Figure 9). With any suspicion of C1C2 mobility, the registration of choice is to C2 in isolation, however, since optimal screw placement within the C2 pars is critical. A cortical breach at this level would endanger the vertebral artery or the cord. A mobile C1 can then be tracked with fluoroscopy. Conversely, fluoronavigation in which fluoroscopic images are acquired and registered in surgical position can be used, but this technique does not provide 3D navigational feedback crucial to avoiding complications during C2 screw placement.

Even though the anatomical landmarks for lateral mass screws are fairly reliable, image-guidance using a 3D CT model can occasionally help avoiding variants of transverse foramen location, thus avoiding injury to the vertebral artery. In cases of normal or increased cervical motility, care must be taken to register each vertebral level separately, or accuracy can suffer greatly. When cervical motility is restricted by a halo vest or some pre-existing fusion it may be reasonable to perform a single registration for multiple levels either by point matching or by surface matching. (Figure 5)

Image-guidance is used more frequently for pedicle screw placement at the cervico-thoracic level, since pedicles here are narrower, making optimal placement of screws more challenging.
Cervical spine: anterior approaches

Image-guidance is used less commonly in anterior cervical approaches in part because the anterior vertebral bodies make an easier target than pedicles, but also because there are less recognisable landmarks that can be used as fiducials for registration. The presence of anterior osteophytes can serve as better landmarks for registration as has been reported11. (Figure 4). Fluoroscopic image-guidance is reported to be particularly useful in approaches to the odontoid for placement of odontoid screws (Figure 10). It must be remembered, however, that the distal fragment may be displaced by the odontoid screw, and that this would be apparent during live fluoroscopy but not with fluoroscopic image-guidance.

The use of fluoroscopic navigation for anterior cranio-cervical decompression is reported, but here again, the advantage of 3D navigation is dependant on CT guidance.55-59 In this situation, the authors prefer CT-based image-guidance using cranial rather than spinal registration software and techniques. Pre-operative CT thus needs to include most of the cranium along with the upper spine in order to enable registration.

Thoracic spine: posterior approaches

Pedicle screw placement in the thoracic spine presents particular challenges due to the narrow anatomy of thoracic pedicles60. There is literature to support the superior results of image-guidance for pedicle screw placement in the thoracic spine14,25. Registration of the posterior thoracic spine is facilitated by the fact that there is relatively little intersegmental movement in the thoracic spine due to the stabilising effect of the ribs. (Figures 11-13). We feel that there is often an advantage of using a pre-operatively acquired volumetric CT for thoracic instrumentation not only because of the registration advantages just discussed, but also because lateral fluoroscopic images by themselves or acquired for an image-guidance system can be of limited quality.

Thoracic spine: anterior approaches

Image-guidance does not have obvious applications in anterior thoracic spine instrumentation, and we have employed this technology only for anterior tumour or kyphus resections, with combined posterior and anterior approaches allowing registration to the posterior spine.

Lumbo-sacral spine: posterior approaches

For routine lumbar and sacral pedicle screw placement, image-guidance using pre-operative CT or intra-operatively acquired fluoroscopy can replace standard fluoroscopy23,61. With relatively well aligned surgical anatomy, image-guidance is less essential, but when minimally invasive percutaneous instrumentation techniques are employed (Figure 14), or if anatomy is very distorted by marked deformity (Figures 15-16) or tumour, image-guidance technology becomes more crucial62-64.
Lumbo-sacral spine: anterior approaches

As with anterior thoracic approaches, we have favoured image-guidance for tumour resection rather instrumentation from this approach.

Applications: tumours

Extradural tumour pathology anywhere in the spine warrants consideration for image-guidance, especially when normal bony anatomy is destroyed. Similar to intra-cranial navigation, it becomes very valuable to be able to anticipate the distance to major nervous and vascular structures when within a tumour that has replaced the normal anatomical landmarks. This is the one time where MRI data are useful to navigation in the spine. Since it is technically difficult to register MRI for spinal surgery, we have acquired volumetric MRI (SPGR, 1.5mm cuts usually with contrast / GE Signa 1.5T) that we co-register or “fuse” with volumetric CT (3mm cuts). (Figure 17) Surgical registration is then performed using the CT data set. This provides both CT data for bone and MRI data for better tumour delineation.

Future perspectives

Imaging technology

Because of the possibility of intersegmental movement between pre-operative CT acquisition (supine) and surgical registration (usually prone), it would be optimal for accuracy to acquire the image-guidance data set at the time of surgery in surgical position. Intra-operative CT would be ideal for this, but is not widely available. Fluoroscopic navigation allows multiplanar views and limits patient and OR personnel radiation exposure, but does not provide detailed 3D anatomical details for surgical guidance. Recently, iso-centric fluoroscopy has provided a hybrid solution by using a dynamic acquisition of the fluoroscopy arm attached to an image-guidance station to provide a CT-like reformatted image. It is likely that further development of this technology will approximate CT more closely.

A growing number of hospitals are acquiring intra-operative MRI. Although bone is poorly defined on MRI, applications for spine tumour surgery will become more interesting, since it will be easier to register MRI at surgery, either directly, or by applying MRI fiducial markers after initial surgical exposure.

Adjunctive technology: impedance-sensitive drilling tools

In order to optimise screw placement, adjunctive technology can be complementary to image-guidance. To improve reliability of pedicle screw placement, a new free-hand,
impedance-sensitive instrument has been developed to provide the surgeon with feedback in the event of a pedicle violation by discriminating changes of tissue impedance at the tip of a drilling instrument⁶. (Figure 18)

The impedance-sensitive instrument consists of an awl instrument with a hollow handle that houses a built-in electronic printed circuit board. Bipolar electrodes situated at the tip of the instrument measure electrical impedance of the tissue as the tip is advanced through the pedicle. The measured impedance is translated into a visible (LED: Light Emitting Diode) and an audio signal to inform the surgeon of impedance changes occurring at the tip of the instrument. Biological tissues have electrical conductivities that depend on tissue structure and blood content. Accurate measure of electrical conductivity should allow discrimination between cortical bone, cancellous bone and soft tissue.

**Radiosurgery**

There has been a significant increase in recent reports of radiosurgery for tumours of the spine⁶⁸,⁶⁹,⁷⁰,⁷¹. Radiosurgery is, of course, image-guided radiation. This field holds promise for the future, but a discussion of radiosurgery is well beyond the scope of this review.

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