The field of spinal surgery has undergone tremendous evolution and rapid technological advances in recent years. Before the appearance of image guidance, surgeons relied on their knowledge of the anatomy of the spine complemented by images acquired pre-operatively and intra-operative fluorescent images. Plain radiography is commonly used to assist in localisation of the skin incision, identification of the proper anatomical level and confirmation of the correct positioning of spinal implants. However, conventional methods such as these have several weak spots, even in the hands of experienced surgeons: experimental and clinical studies have revealed pedicle screw misplacement rates of up to 20–30% using these techniques. In contrast, image guidance provides 3D visualisation of the spine, which can be used for pre-operative planning and intra-operative navigation, as well as for the confirmation of the accurate localisation of concealed anatomical spinal structures that are cannot be directly visualised during standard surgical exposures and fluoroscopy. This article provides a short review of the different types of intra-operative imaging, underlining the general opinion of the current literature: that image guidance enables highly accurate intra-operative navigation with increased safety in complex spinal procedures. There are three commonly used methods of spinal image guidance: pre-operative computed tomography (CT)-based image guidance, fluoroscopy-based image guidance and intra-operative 3D fluoroscopy. At our institution we use the CT-based and intra-operative 3D methods; therefore, this article will focus on these two techniques.

**Computed Tomography-based Image Guidance**

Prior to surgery, a CT scan is taken of the relevant region of the spine, using thin axial slices (1–2mm). The data from this scan are transferred to the computer workstation through a local network connection. The data are then prepared for use in the navigation system in the operating room (OR) and transferred to the OR system using a hardware carrier. The OR system consists of several components, including an electro-optical camera array, a surgical reference system (dynamic reference array, DRA) and various customised spinal instruments, for example awls. The optical tools are connected to the instruments and the DRA and are tracked by the camera array in order to calculate their position in 3D. In addition, there is a computer workstation that runs the system software and functions as the primary system interface. The system software consists of programs able to transfer CT data to the workstation, as well as registration and surgical planning options. The next step is patient registration, which provides a correlation between the operative anatomy and the pre-operative CT anatomy as shown on the monitor. In order to perform the registration, a navigation clamp (DRA) is fixed on the spinous process of the vertebra. Two different methods of registration are possible: surface matching or CT fluoro matching. For surface matching, the registration begins by determining a start point on the spinous process and choosing eight specially prescribed anatomical points (the superior facet, the inferior facet and the base and tip of the spinous process on both sides) of the selected vertebra with a registration probe. This is supplemented by a process in which 12 random points are selected on the exposed surface of the vertebra. This provides the navigation system with a contour map of the vertebra. The computer workstation then quantifies the registration error as an index for the accuracy of the matching procedure between the surgical anatomy and the computer display. The consensus in the literature is that registration errors <1.5mm can be accepted for most spinal procedures; however, we always aim for a registration error <1.0mm in the cervical region, as well as in the upper and middle thoracic regions (see Figure 1a).

For CT fluoro matching, anterior–posterior and lateral fluorescent images are obtained using the C-arm. The C-arm is fitted with a calibration target during the image acquisition. The computer workstation uses these images to obtain a congruent result with the pre-operative CT data (see Figure 1b). After both matching procedures, before any navigation is attempted anatomical verification of the registration accuracy must be performed. This verification is achieved by touching the registration probe to several points on the selected vertebra and ensuring that the virtual probe is seen to be touching the corresponding points on the multiplanar displayed CT images on the monitor. The awls or other special tools can then be calibrated. Navigated pedicle preparation is particularly useful in small pedicles, for example in the mid-thoracic spine and the cervical spine (see Figure 2). Anterior procedures, such as resection of posterior wall fragments in
unstable fractures with neurological impairment, can also be performed using image guidance (see Figure 3). Despite the outstanding image quality of CT-based navigation, this technique has some distinct disadvantages. A pre-operative CT scan using a particular protocol is required, with associated time costs. Sometimes a repeat scan is needed, especially when the patient was scanned for diagnostic reasons with a navigation-incompatible protocol in another hospital. Time is also needed for pre-operative preparation of the data sets. Furthermore, there is a learning curve for the procedure of identification and registration of the anatomical landmarks. Complex anatomical structures or a lack of precise bone landmarks can lead to a prolongation of the registration progress and therefore of the operation time. As the CT is taken prior to the operation, inter-segmental relationships are not presented and therefore changes between status at the time of the scan and status at the time of the operation can be overlooked.

Navigation with 3D C-arm Fluoroscopy

3D fluoroscopy is a significant improvement in the rapidly developing sector of image guidance. In contrast to a standard fluoroscope, a C-arm is able to automatically rotate around the patient while maintaining the pertinent spinal anatomy at its centre. Used in conjunction with specialised software, the C-arm can function as a kind of CT scanner. It takes almost exactly one minute for the automated image acquisition; these images are then reconstructed to provide axial, coronal and sagittal images of the spine. During the scan, an apnoeic phase is required, otherwise the breathing motion causes a reduction of image quality. Loss of accuracy caused by respiration has been measured to be up to 1.3mm in the lumbar spine, and even greater in the thoracic spine. The C-arm is fitted with a calibration target and the DRA is attached to the patient. The camera is then able to track the position of the DRA in reference to the C-arm while the image acquisition is performed. Reconstructed images are transferred to the navigation system’s computer workstation and automatically uploaded into the navigation software. An anatomical registration for the navigation is not necessary. Nevertheless, verification of registration has to be performed in the same way as in CT-based navigation before the navigation can start (see Figure 4). There are many advantages of this innovative technique, although image quality is still not as high as in conventional CT. Stockle et
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Figure 4: Navigated Screw Placement in T4 and Post-operative Computed Tomography Control in a Patient with Osteolytic T5 Metastasis and Spinal Canal Compromise

Figure 5: Intra-operative Control with 3D Fluoroscope After Screw Fixation of an Unstable Odontoid Fracture (Anderson/D’Alonzo II)

al. stated that their experiences were very positive, and the system was extremely reliable and precise in their experimental and clinical trials. Over the course of 160 drilling procedures, they reported a failure rate of only 4.2%.8 The problem of navigation inaccuracy due to inter-vertebral alignment differences between the pre-operative CT data set and the intra-operative image presentation is eliminated. Since the system can display up to three adjoining vertebrae at once, separate registration solutions appear not to be necessary. The need for a pre-operative CT scan with a specific image-guided protocol is eliminated, along with its associated financial and time costs; this is also true of the time-consuming pre-operative work on data sets. Furthermore, the need for anatomical registration is completely abolished, as navigation can start immediately after the images have been transferred to the workstation. Finally, a post-operative control scan can be taken in the OR to ensure the accuracy of implant placement (see Figure 5). Incorrect screw placements can thus be corrected immediately, saving time and avoiding expensive revisions.7.8 The main disadvantage is the high cost of the system; it may also be necessary to make other purchases, for example a carbon operation table as metal artefacts affect image quality.

Comparison of Image-guidance Techniques and Non-navigation Screw Placement

There are many investigations – both clinical and in laboratories – that have analysed the accuracy of commonly used navigation techniques. Kosmopoulos et al. drew up a meta-analysis of the current literature and found that navigation provided higher accuracy in the placement of pedicle screws for the sub-groups presented. Overall, the median placement accuracy in the in vivo navigation-assisted sub-group (95.2%) was higher than that in the unnavigated subgroup (90.3%). The report included 130 studies with a total of 37,337 implanted pedicle screws.10 Amniot et al.11 compared 100 patients who underwent placement of pedicle screws (T5–S1) using conventional fluoroscopy with 50 patients who were operated on using pedicle screw placement (T2–S1) using computer-assisted image guidance. In the conventional fluoroscopy group, 461 of 544 screws (85%) were found to be accurately placed compared with 278 of 294 screws (95%) in the computer-assisted image-guided group. The issue of the radiation dose for both the patient and the surgeon is still the topic of many investigations. In a comparison between navigation with 3D rotational radiographic data and fluoroscopic guidance, Von Walsum and his workgroup12 analysed radiation exposure at the surgeons’ hands and measured lower values for 3D rotational radiography. Although the vast majority of the literature emphasises the increased safety and accuracy of image-guided spinal surgery, it is important to be aware of potential problems with each of the modalities. These concern data acquisition through to data transfer and data set preparation and, in particular, the intra-operative use of computer navigation. In addition, software and hardware problems can slow down the workflow. Those who are beginning to use such systems should undergo a specialised introductory training course, ideally followed by supervised training from surgeons who are sufficiently experienced and well-informed about the possible sources of error. Only then will the identification and subsequent avoidance of complications in image-guided navigation be possible.13

Conclusions

Intra-operative spinal image guidance has evolved rapidly in the last few years. Through the technical improvement of navigation systems, the safety of spinal procedures – especially in critical regions with small pedicles, such as the cervical spine and the upper and middle thoracic spine – could be increased. The new development of intra-operative 3D image guidance can be seen as a potentially important tool in spinal surgery. As with all novel technologies there is a learning curve, which can be overcome with training and experience.