INTRODUCTION

Computers are becoming pervasive in all fields of human endeavor, and medicine is no exception. Starting with the advent of computed tomography (CT) in the 1970s, computer-based systems have become the standard of care in many clinical fields, most notably in radiology, radiation therapy, neurosurgery, and orthopedics. These systems assist the surgeon in planning, executing, and evaluating the surgery, often improving existing procedures and at times enabling new procedures that could not have been realized without them.

The first computer-based systems for surgery were developed in the mid 1980s for neurosurgery. The key characteristic of these systems was an integration of preoperative information with intraoperative execution. Traditionally, preoperative radiographs, CT scans, and magnetic resonance images (MRIs) showing the patient’s condition and the planned approach are brought into the operating room to guide the surgeon. However, when performing surgical actions, it is not possible to determine exactly where the surgical tools and implants are with respect to these images, especially when direct line of sight is limited, such as in keyhole, minimally invasive, and percutaneous surgery. Often, intraoperative images, such as fluoroscopic radiographs, are acquired to monitor the location of tools, implants, and anatomy. The surgeon must then mentally recreate the spatio-temporal situation from these images and decide on a course of action. This mental integration is qualitative and imprecise, as is the surgeon’s hand-eye coordination, which requires significant skill, experience, and judgment and varies from surgeon to surgeon.

Computer-aided surgery (CAS) systems perform this integration automatically and accurately, thereby providing the surgeon with a precise, more complete, and up-to-date view
of the intraoperative situation.\(^2\) By incorporating real-time tracking of the location of instruments and anatomy, and their precise relation to preoperative and intraoperative images, the systems create a new modality akin to continuous imaging. In this sense, CAS systems are like navigators based on global positioning systems (GPSs), currently found in cars that help drivers find their way to a desired destination. During driving, the system shows the exact location of the car at all times on a computerized map and provides turn-by-turn directions ahead of time.

In orthopedics, the first CT-based navigation commercial systems were introduced in the mid 1990s for spinal surgery.\(^2\) Several years later, fluoroscopic radiography-based systems were developed for total hip and total knee replacement.\(^3\)

Today, a variety of image-free and image-based systems exist for planning and executing a variety of orthopedic procedures, including primary and revision total hip and total knee replacement; anterior cruciate ligament reconstruction; spinal pedicle screw insertion; and trauma.\(^4\,9\)

CAS has already become an integral part of the orthopedic trauma surgery set-up. The rapid advancement in the use of computers in this field provides many feasible options at all stages of treatment of the orthopedic trauma patient, from preoperative planning to postoperative evaluation. The role of computerization in the treatment of trauma patients is not only to enhance the surgical options in the preplanning stage but also to shorten surgery, an advantage that could be crucial for patient morbidity in a trauma set-up. Although computerized imaging equipment can be moved into the admitting area and/or the trauma unit of the emergency department, this may involve adaptation of an existing set-up, requiring administrative changes and incurring high costs. Another option is the use of comprehensive imaging provided by the improvement of conventional image intensifiers in achieving accurate three-dimensional (3D) information in a minimal period of time inside the operating room, such as can be achieved with isocentric fluoroscopy and mobile CT-like machines.

Computerized navigation has thus been a key factor in expanding the use of CAS from the preplanning to the intraoperative stage. This expansion integrates well with the current tendency toward minimal invasive surgery. CAS technology brings important digitized information into the operating room, enabling the accomplishment of three main goals: minimal invasive surgery, maximal accuracy, and robustness. Moreover, both surgeon and patient benefit from a significant reduction in the amount of radiation exposure usually associated with orthopedic trauma surgery. The main modality, which is currently in various stages of application and has been adapted to trauma surgery, is fluoroscopy-based navigation including modern mobile 3D image intensifiers. While this technology might be viewed by some as only improved fluoroscopy, it is undoubtedly this modality that has allowed computer-based navigation systems to become a pioneer in the process of CAS integration into the orthopedic trauma operating room.

### TECHNICAL ELEMENTS

Computer-aided orthopedic surgery in skeletal trauma (CAOS-ST) systems consist mainly of preoperative planning, when available and feasible, and intraoperative navigation. Robotic and verification technologies are still experimental and at present are only seldom used.\(^3\) We will describe the technical principles of each and the existing types of navigation systems.

### Computerized Preoperative Planning and Model Construction

Preoperative planning for skeletal trauma surgery has traditionally been accomplished using radiographic and CT films. The drawbacks of this traditional practice are that anatomic measurements are either approximate or cannot be obtained; that fixation plates and implant templates are usually not available; that the size, position, and orientation of the implants can only be approximately determined; and that spatial views are unavailable. Consequently, only a few surgical alternatives can be explored.

Digital radiographic and CT data have significantly improved and allow for better planning. Digital radiographic images can be correlated and anatomic measurements, such as anteverision angle and leg length, can be performed on them. Digital templates of fixation and implant devices can be superimposed onto the radiographic images to explore a variety of alternatives. Computer-aided planning packages allow surgeons to select digital templates of fixation devices, position them, and take appropriate measurements. This computerized support allows for greater accuracy, versatility, and simplicity as compared with traditional analog templating and measuring techniques.\(^10,11\)

Figure 18-1A shows a screenshot of a preoperative planning session for internal fixation of a fractured tibia.

For CT data, preoperative planning allows for 3D measurements and spatial visualization of complex structures and fractures. It allows for the construction of computer models, such as bone surface mesh, anatomic axes, and osteotomy planes. Bone fragment models and implants can be visualized in three dimensions and manipulated to analyze several possible scenarios. The resulting fixation can be evaluated in three dimensions and with a simulated postoperative radiograph, known as a digitally reconstructed radiograph, obtained from the preoperative CT in cooperation with templates of fixation hardware. In certain situations the healthy side can be inverted (“mirror image”) and can be used for templating of the fractured side. Figures 18-1B(1 to 4) illustrate the concepts of preoperative planning in reduction and fixation, as well as applying virtual forces using finite element analysis of a humeral fracture.

An increasing number of computer programs have been developed enabling visualization of virtually all steps of the real surgical procedure; however, clinically it is mainly two-dimensional (2D) technology that is available.\(^12,13\) This ability to exercise a virtual surgical procedure marking out safe zones allows for precise planning of screw dimensions and pathways and enables prechecking of the percutaneous option as an alternative to the open approach.
There is consensus among most orthopedic surgeons that preplanning is mandatory and that it helps to improve performance.

**Principles of Navigation and Guidance**

The goal of navigation is to provide precise, real-time visual feedback of the spatial location of surgical instruments and anatomic structures that cannot be directly observed. In current practice, this information is obtained by repeated use of fluoroscopic radiography, which produces a time-frozen 2D view; is not updated in real time; and results in cumulative radiation to the surgeon, staff, and patient. The goal of guidance is to indicate to the surgeon in real time, via images, graphics, or sound, the best course of action during surgery.

Navigation systems show the current location of surgical instruments with respect to images of the anatomy using either preoperative CT or intraoperative fluoroscopic radiography.
images and continuously update the image as the instruments and bone structures move. The resulting display, called navigation images, is equivalent to continuous intraoperative imaging without radiation.

Navigation requires tracking, registration, visualization, and validation. Tracking determines in real time the location of moving objects in space. Registration establishes a common reference frame between the moving objects and the images. Visualization creates navigation images showing the location of moving objects with respect to the anatomy. Validation ensures that the updated images match the clinical intraoperative situation.

The key advantage of navigation is that it obviates the need for repeated fluoroscopic radiography. However, it requires additional procedures, including setting up the navigation system and attaching trackers to both instruments and bone structures of interest, as well as additional surgical training.

System Components and Mode of Operation

A navigation system consists of a computer unit, a tracking unit, and a tracker mounting hardware. Figure 18-2 shows the equipment set-up in the operating room. A rolling cart usually holds the computer unit and the tracking base unit. The cart is placed next to the patient, so that the surgeon can conveniently see the display. Tracking requires a position sensor and one or more trackers. The position sensor determines the spatial location of the trackers at any given moment in time. By attaching trackers to surgical tools and bone structures, their relative spatial position can continuously be followed and updated in the computer display. Trackers are rigidly mounted on tools and bones with tracker mounting jigs, which are mechanical jigs similar to screws and clamps. Because the trackers and their mounting jigs come in contact with the patient, they must be sterilized. The position sensor is either mounted on the cart, part of a separate unit, or attached to the ceiling or to a wall. It is aimed at the surgical field so that the expected tracker motions are within its working area throughout surgery. The position sensor’s location can be changed during surgery as needed. When fluoroscopic radiography images are used for navigation, the computer unit is also connected to a C-arm and imports images acquired with it. The C-arm is usually fitted with its own tracker to determine its relative location with respect to the tracked objects and imaged anatomy.

The tracking base unit receives and integrates the signals from the position sensor and the trackers. The computer integrates the signals from the base unit with fluoroscopic radiography or CT images and instrument models (registration), and creates one or more views for display (visualisation). The navigated images are updated in real time by the computer as the instruments and anatomy move. The tool calibration unit is used to obtain geometric data of surgical tools fitted with trackers, such as the tool tip’s offset. These geometric data are used to create the instrument model for display.

Tracking

A tracking system obtains the position and orientation of trackers by measuring spatially dependent physical properties, which can be optical, magnetic, acoustic, or mechanical. Currently, two types of tracking technologies are available for medical applications: Optical and magnetic, with optical being by far the most commonly used (Fig. 18-3).

Optical Tracking

In optical tracking, the position sensor consists of two or more optical cameras that detect the light emitted or reflected by markers. Each camera measures the distance of the markers from the camera. Because the base distance between the optical cameras is known, the position of the marker with respect to the camera’s base line can be computed by a method known as triangulation. A tracker consists of three or more markers mounted on a rigid base (Fig. 18-3A). The tracker’s position and orientation are determined by the markers’ positions relative to each other and by their sensed position with respect to the position sensor. A key requirement is the maintenance of an unobstructed line of sight between the position sensor and the trackers. Optical tracking systems can be active, passive, or hybrid.

Active Tracking

Active tracking uses active markers, which are light-emitting diodes (LEDs) that are strobbed (turned on and off) in tandem
by the base unit. LEDs emit infrared light that is detected by the cameras. The cameras’ capture is synchronized with the LED strobbing so that the identity of the lighting marker is known. Active trackers consist of three or more wired LEDs mounted onto a rigid base and connected by a cable or by a wireless link (tetherless communication) to the tracking base unit. Each active tracker has a unique identifier. Active trackers are built so that they can be sterilized many times over.

**Passive Tracking**

Passive tracking uses passive markers, which can be reflective spheres or printed patterns (Fig. 18-3B). Reflective spheres reflect the infrared light generated by the position sensor, which is then detected by the cameras. Unlike the active markers, passive markers are not controlled by the tracking base unit and are “seen” simultaneously by the cameras. Passive trackers consist of three or more passive markers. The identity of the passive tracker is determined by the configuration of the markers on the rigid mounting base. Consequently, no two passive trackers can have the same marker configuration. The tracking base unit must know the tracker configuration. Because the markers lose their reflectance with sterilization and touch, they must be replaced after several uses.

**Hybrid Tracking**

Hybrid tracking incorporates both active and passive tracking. Hybrid tracking systems simultaneously track both passive and active trackers, thus providing the advantages of both technologies. Table 18-1 summarizes the advantages and disadvantages of active (wired and tetherless) and passive trackers. Because neither technology is always superior to the other in all categories, the anatomy, the surgical instruments, and the clinical situation determine the best choice of trackers.

In terms of physical characteristics, passive trackers are lightest, while tetherless active trackers are heaviest because of the battery required to activate the circuitry and the LEDs. Passive trackers are more rugged than active ones because they have no electronics. Tetherless trackers are more convenient because there

**FIGURE 18-3** Trackers. **A**: Active optical tracker. **B**: Passive optical tracker. **C**: Magnetic tracker. (Courtesy of Traxtal Technologies, Toronto, Canada.)
are no cables to get in the way. In terms of functionality, active
trackers have the advantage that they indicate, on the tracker
itself (via a light indicator), when the line of sight is maintained,
while passive tracker obstruction can only be shown on the display.
Active trackers are automatically recognized as soon as they
are plugged in. Passive trackers are the most reliable, because
there are no electric connections; tetherless active trackers are
the least reliable because of possible communication interfer-
ences and their short battery life (LEDs require substantial power
for illumination). In terms of performance, active trackers are
somewhat more accurate than passive trackers but they are also
more sensitive to their orientation with respect to the cameras.
In terms of cost, it is the highest for active tetherless tracking
because of the additional electronics and lowest for passive track-
ers, which have no electronics at all. The running cost of active
wired tracking is lowest, because there are no batteries or reflec-
tive spheres to replace. The amortized cost over time of the wired
active trackers represents significant savings.

Magnetic Tracking
Magnetic tracking works by measuring variations of generated
magnetic fields. The position sensor consists of a magnet that
generates a uniform magnetic field and a sensor that measures its
phase and intensity variations. Trackers consist of one or
more miniature coils mounted on a rigid base that generate a
local magnetic field from an electric current, either alternating
or pulsed direct (Fig. 18-3C). Both the position sensor and the
trackers are connected to the tracking base unit. The tracker
magnetic field modifies the sensor’s magnetic field character-
istics according to its position in space. The location of the
tracker is computed from the relative variations of the sensor’s
intensity and its phase magnetic field. A key requirement is the
maintenance of a uniform magnetic field, which is altered by the
vicinity of magnetic fields from other electronic devices and
by nearby ferromagnetic objects.

Magnetic trackers are usually much smaller, lighter, and
cheaper than optical trackers and their functionality is similar
to that of active optical trackers (Table 18-1). However, the
accuracy of existing magnetic tracking systems is less than that
of optical tracking systems. Their main advantages are that they
are small and do not require a direct line of sight, and there-
fore they are useful in percutaneous procedures. However, they
do require careful control of the environment in which they
operate, because the nearby presence of ferrous objects and
electrical instruments in the operating room can influence their
measurements.

Tracking: Technical Issues
The best way to visualize a tracking system is as a 3D measure-
ment instrument, also known as a coordinate measuring machine. A
3D measurement instrument provides a stream of spatial location
measurements in a given range, accuracy, and rate (frequency).
It measures the location of an object (a tracker) with respect to
a fixed coordinate frame centered at the position sensor’s origin.
The location of an object in space, its position and orientation, is uniquely determined by six parameters: three translational (vertical, horizontal, and depth) and three rotational (roll, yaw, and pitch).

Tracking systems measure the position of markers in a predefined volume in space, called the tracking work volume. Its shape is usually simple, such as a sphere, pyramid, or cube, depending on the type of position sensor technology used. The distance between the position sensor and the tracking work volume center is fixed.

Accuracy is defined as the measure of an instrument’s capability to approach a true or absolute value. Accuracy is a function of both bias and precision (Fig. 18-4). Bias is a measure of how closely the mean value in a series of replicated measurements approaches the true value. Precision is a measure of how closely the values within a series of replicated measurements agree with each other. It has no units and indicates the relative degree of repeatability. Repeatability is a measure of resolution and stability. Resolution is the smallest discernible difference between two measurements. Stability refers to making identical measurements at a steady state and over a sufficiently long period. Frequency is the number of overall measurements per second. Static accuracy refers to measurements obtained when the trackers are at rest, while dynamic accuracy refers to measurements obtained as the trackers move.

The factors influencing tracking accuracy are as follows.

Position sensor accuracy: For optical tracking, the number of cameras, the distance between them, and their resolution. For magnetic tracking, the intensity of the magnetic field and the resolution of the magnetic sensor.

Marker accuracy: For optical tracking, the type of LEDs or sphere size and reflectance. For magnetic tracking, the strength of the coil magnetic field.

Tracker accuracy: Depends on marker accuracy, number of markers, their configuration, and the distance between them.

Tracking system accuracy: Depends on all of the above, and on the relative position and orientation of the position sensor with respect to the trackers.

It should be noted that accuracy is not uniform within the tracking work volume. It is usually highest at the center, with decay toward the boundaries of the tracking work volume. Therefore, the position sensor should always be placed as close as possible to the center of the expected operating volume. It is often useful to distinguish between position and orientation accuracy. Statistics on accuracy include average, minimum, maximum, and root-mean-square (RMS) error. Table 18-2 summarizes the typical characteristics of current tracking systems.

### Tool and Bone Tracking

Tool and bone tracking are achieved by rigidly attaching trackers to them with mounting hardware (Fig. 18-5). To track a surgical tool, a tracker can be added to it or the tool can be custom designed, with markers integrated within the tool. To track the C-arm, a ring with several dozen markers is attached to its image intensifier. It is very important that the trackers do not move with respect to the tracked body during surgery.

### Table 18-2 Typical Characteristics of Commercial Tracking Systems

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Optical</th>
<th>Magnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Active</td>
<td>Passive</td>
</tr>
<tr>
<td>Work volume</td>
<td>Sphere</td>
<td>Sphere</td>
</tr>
<tr>
<td></td>
<td>1 m³ diameter</td>
<td>1 m³ diameter</td>
</tr>
<tr>
<td>Distance from center</td>
<td>2.25 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Accuracy (root-mean-square)</td>
<td>0.1–0.35 mm</td>
<td>0.35 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>60–450 Hz</td>
<td>60–250 Hz</td>
</tr>
<tr>
<td>Interferences</td>
<td>Line of sight</td>
<td>Line of sight</td>
</tr>
<tr>
<td>Number of tools</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

**Figure 18-4** Accuracy and bias. Accuracy is a combination of precision and bias. High accuracy requires no bias and high precision (top right). The concentric circles represent the distance from the true value (the common center of the circles); dots represent actual measurements. (Image property of authors.)
FIGURE 18-5  Trackers and mounting hardware. A: Bone clamp attached to spinous process. B: Bone screw attached to femur. C: Bone screw and extender attached to pelvis. D: Trackers on surgical drill and screwdriver. E: Ring tracker on C-arm image intensifier. (Photographs A, B, D, courtesy of Traxtal Technologies, Toronto, Canada; C, courtesy of MedVision, Unna, Germany; E, property of authors.)
because relative movement cannot be detected and measured and will increase system error.

Registration

Registration is the process of establishing a common reference frame between objects and images. It is a prerequisite for creating a reliable image of the intraoperative situation, accurately showing the relative locations of the anatomy and the surgical tools of interest with respect to the preoperative and/or intraoperative images. Registration is achieved by transformations between the objects’ coordinate frames at all times.

A coordinate frame serves as a reference within which the spatial locations (position and orientation) of objects can be described. Each object of interest has its own coordinate frame. The relative location of objects is described by a transformation \( T_0^1 \), describing the location of B’s coordinate frame with respect to A. A transformation is a matrix describing the relationship between the three rotational and three translational parameters of the objects. The transformation is static (constant) when the relative locations of A and B do not change or dynamic \( T_0^1(t) \) (a function of time \( t \)) when one or both of the objects move. The relative locations of objects are obtained by chaining (composing) transformations. Thus, the location of \( C \) with respect to \( A \) is obtained from the location of \( B \) with respect to \( A \) and the location of \( C \) with respect to \( B \):

\[
T_A^C = T_A^B \circ T_B^C
\]

The goal is to compute the location of the surgical tools with respect to the displayed images \( T_{\text{display}}^i(t) \), as illustrated in Figure 18-6. This registration involves four types of transformations: (1) tracker transformations; (2) tool transformations; (3) image transformations; and (4) display transformations.

1. Tracking transformations: Tracking transformations \( T_{\text{tracker}}^i(t) \) indicate the location of each tracker with respect to the position sensor coordinate system. They are provided in real time by the tracking system and can be static or dynamic, depending on whether the objects attached to the tracker move or do not move. The relative location of one tracker with respect to the other is obtained by chaining their transformations:

\[
T_{\text{sensor}}^{\text{tracker}_1}(t) = T_{\text{sensor}}^{\text{tracker}_2}(t) \circ T_{\text{sensor}}^{\text{tracker}_1}(t)
\]

where \( T_{\text{sensor}}^{\text{tracker}_1}(t) = [T_{\text{sensor}}^{\text{tracker}_2}(t)]^{-1} \) is the inverse transformation.

2. Tool transformations: Tool transformations \( T_{\text{tool}}^{\text{tracker}} \) indicate the location of the tool coordinate frame with respect to the tracker. Because the tracker is rigidly attached to the tool, the transformations are static. They are provided at shipping time when the tracker and the tool come from the same manufacturer (i.e., precalibrated tools). Alternatively, they are computed shortly before surgery with a tool calibration procedure, which typically consists of attaching the tool to a tracked calibration object and computing with custom calibration software the transformation and the tool’s geometric features, such as its main axis and tip position.

3. Image transformations: Image transformations \( T_{\text{image}}^{\text{sensor}} \) indicate the location of the images with respect to the position sensor. There are two types of transformations, \( T_{\text{CT}}^{\text{sensor}} \) and \( T_{\text{x-ray}}^{\text{sensor}} \), depending on the type of images used: Either one preoperative CT or several intraoperative fluoroscopic radiography images. The transformation between the position sensor and the CT image \( T_{\text{CT}}^{\text{sensor}} \) is static and unknown and must be computed with a CT registration procedure. The transformation between the position sensor and fluoroscopic radiography images \( T_{\text{x-ray}}^{\text{sensor}} \), where \( i \) indicates each C-arm viewpoint, is computed from the transformation \( T_{\text{tracker}}^{\text{image}} \) of the ring tracker attached to the C-arm image intensifier transformation and \( T_{\text{x-ray}}^{\text{tracker}} \), the C-arm internal imaging transformation:

\[
(T_{\text{x-ray}}^{\text{image}}) = (T_{\text{image}}^{\text{sensor}}) \circ (T_{\text{x-ray}}^{\text{tracker}})
\]
In older fluoroscopic units, this internal transformation is orientation-dependent and thus must be computed for each C-arm viewpoint i.

4. **Display transformations**: Display transformations \( T_{\text{display}} \) and \( T_{\text{image}} \), indicate the location of the CT and fluoroscopic radiography images with respect to the display shown to the surgeon, respectively. The transformations are determined by the viewpoint shown to the surgeon. Note that the transformation between the bone and the tracker \( T_{\text{bone}} \) is unknown and cannot be computed, because the exact location of the tracker mounting jig with respect to the bone is not known. Instead, the relative location of the tool with respect to the tracker is used:

\[
T_{\text{tool}}(t) = T_{\text{sensor}}(t) \cdot T_{\text{tracker}}(t) \cdot T_{\text{tool}}
\]

In effect, the bone tracker becomes the reference coordinate frame and therefore is also called the **dynamic reference frame**.

The registration between the tool coordinate frame and the display coordinate frame \( T_{\text{display}}(t) \) is computed by chaining the transformations:

\[
T_{\text{display}}(t) = T_{\text{image}} \cdot T_{\text{sensor}} \cdot T_{\text{tracker}} \cdot T_{\text{tool}}
\]

For fluoroscopic radiography images, there is one transformation \( T_{\text{image}} \), and \( T_{\text{tool}}(t) \) for every C-arm viewpoint i.

**Registration Accuracy**

The accuracy of the registration depends on the accuracy of each transformation and on the cumulative effect of transformation chaining. Because the transformation includes rotation, the translational error is amplified as the distance from the reference frame increases (Fig. 18-7).

Tracking transformation accuracy depends on the accuracy of the tracking system and on the location of the tracker with respect to the center of the position sensor working volume. Tool transformation accuracy depends on the accuracy of the tool calibration procedure and on the relative location of the tracker with respect to the tool tip. Image transformation accuracy depends on the accuracy of the imaging modality used and on the tracking system’s accuracy. For CT images, it depends on the resolution (slice spacing and pixel size) of the CT scan and on the accuracy of the CT registration procedure. For fluoroscopic radiography images, it depends on the C-arm calibration and on distortion correction procedures. Display transformation accuracy is very high, as it only involves numerical computations.

Note that any accidental shift in the location of the bone tracker with respect to the bone will introduce an error in the registration. It is therefore essential that the bone tracker remain rigidly secured to the bone at all times during navigation.

**Visualization**

Visualization creates updated images that show the location of moving objects with respect to the anatomy. The navigation images are created by merging the preoperative and intraoperative images with the tools and bone location information. The navigation images can be augmented with relevant procedure-dependent data, such as anteversion angle and distance from a predefined safe zone.

The type of navigation images created depends on the preoperative and intraoperative images that are used, on the surgical tools, and on the surgical procedure. In fluoroscopic-based navigation systems, the navigation images consist of fluoroscopic radiography images from the C-arm typically used in conventional surgical procedure poses (anterior–posterior, lateral, oblique), with the surgical tool silhouette at its present location superimposed on them. For example, when the tool is a long cylinder (e.g., drill, pointer, or screwdriver), the tool’s location and its prolongation are displayed in two different colors to indicate what would be the tool’s location if the current directions were followed. The number of images, tool silhouette, and additional navigation information are procedure-dependent.

In CT-based navigation systems, the navigation images typically consist of sagittal, coronal, and transverse CT cross sections, and a spatial view with the preoperative plan (e.g., fixation screws, fixation plate at their desired location), with the

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**FIGURE 18-7** Influence of the angular error on the translational offset. A dynamic reference frame is attached to the proximal femur. With an angular transformation error of only 1 degree, a nearby target (1) 50 mm from the origin of the bone coordinate frame will be offset by 0.9 mm (1'), which is acceptable in most situations. However, a farther target (2) 150 mm away will be offset by 2.6 mm (2'), which may not be acceptable. (Image property of authors.)
surgical tool’s silhouette at its current location superimposed on them. Typically, the tool tip corresponds to the crosshair location in the CT cross sections.

Visualization software usually provides the surgeon with various image processing, viewpoint selection, and information display features such as contrast enhancement, viewpoint rotation and translation, window selection, and tool silhouette thickness and color control.

**Validation**

Validation is the task of verifying that the images and data used for intraoperative navigation closely correspond to the clinical situation. It is essential to verify and quantify the correlation; otherwise the data can mislead the surgeon and yield unwanted results. Validation is an integral part of the navigation surgical protocol. It is performed both before the surgery starts and at key points during the surgery.

There are three main types of verification.

1. **Tool calibration verification**: Verifies that the tool’s geometric information is accurate. Sources of inaccuracy include deformations in the tool as a result of high-temperature sterilization; bending; wear and tear; tracker relative motion; and marker drift.

2. **Dynamic reference frame verification**: Verifies that the bone tracker has not moved with respect to the bone to which it is attached.

3. **Registration accuracy verification**: Verifies that the tool, implant, and bone fragment locations are indeed where they are shown in the navigation images. Over time, registration accuracy depends on variations in the tool’s calibration accuracy; on the dynamic reference frame’s relative location with respect to the bone to which it is attached; on the tracking system’s drift over time; and on the accumulation of small computational numerical errors.

The validation procedure depends on the type of surgery, the navigated surgical tools, and the images used. Tool calibration verification usually consists of verifying with a calibration jig that the tool tip is at the computed location. Dynamic reference frame and registration accuracy verification usually consist of verifying that the tracked bones and tools are indeed where the navigated images indicate. This is done by acquiring one or more fluoroscopic radiography images and comparing them with the navigation images. Alternatively, it is done by touching with the tip of a surgical tool the known anatomic landmarks and verifying that the tool tip appears close to the landmark in the navigated image. Registration accuracy is quantified by measuring the drift between the actual and the computed location of tools and anatomic landmarks. When registration accuracy is inadequate, the surgeon must repeat the registration process.

**NAVIGATION SYSTEMS**

There are currently two types of navigation systems for CAS in skeletal trauma: Fluoroscopy-based and CT-based navigation systems.

**Fluoroscopy-based Systems**

Fluoroscopy-based systems create navigation images by superimposing the surgical tool silhouette onto conventional fluoroscopic images and updating its location in real time, thereby creating the impression of continuous fluoroscopy without the ensuing radiation. The resulting effect is called virtual fluoroscopy. Fluoroscopy-based systems are thus closest to the current practice of conventional fluoroscopy because the navigation images are in close proximity to the familiar fluoroscopic images, with the advantage being that only a dozen fluoroscopic radiography images are used, instead of tens or even hundreds.

There are two types of fluoroscopy-based navigation systems: Systems that use conventional C-arm fluoroscopy and those that use new 3D fluoroscopy, such as the Siemens Iso-C 3D C-arm. Virtually any C-arm can be used, provided that the images are corrected for geometric distortion and the C-arm imaging properties are calibrated. The correction is usually done with an online C-arm calibration procedure that relies on imaged patterns of metallic spheres mounted on the C-arm ring tracker (the spheres appear as a grid of black circles in the images). Newer conventional and 3D C-arms do not require calibration.

**Conventional C-arm Fluoroscopy**

The surgical protocol is as follows: Shortly before surgery, the rolling cart with the display, computer unit, and tracking base unit is positioned in the operating room so that the display can be easily seen by the surgeon. The position sensor is positioned so that it does not get in the way and its working volume is roughly at the center of where the surgical actions will take place. Next, the ring tracker is mounted on the C-arm’s image intensifier and covered with a transparent plastic for sterility. The patient is then brought into the operating room and surgical preparations proceed as usual. Next, the surgeon validates the tool calibration and installs the dynamic reference frame with tracker mounting hardware. Touching known anatomic landmarks with the tip of a surgical tool and verifying that the tool tip appears close to the landmark in the navigated image validates the registration. Once registration validation is successful, the navigated surgery begins. At key points during surgery, such as before drilling a pilot hole or inserting a fixation screw, one or more validation fluoroscopic radiography images can be taken to verify that the navigated images correspond to the actual situation. The navigation procedure can be repeated with other tools and implants. At any time during the procedure, the navigation system can be stopped and the procedure can continue in a conventional manner.

**Three-dimensional Fluoroscopy**

3D fluoroscopy is a new imaging modality that allows for the acquisition of CT-like images during surgery by taking about 100 fluoroscopic radiography images at one-degree intervals with a motorized isocentric C-arm. This fluoroscopic machine can also be used as a conventional C-arm, with the added advantage that CT and fluoroscopic radiography images acquired with it are already registered. Although these images are not of as high a quality as those obtained with a preoperative CT, and can only be used to image limbs, the radiation dose is
about half of the dose of a regular CT and accurately reflects the actual intraoperative situation. The navigation images consist of both CT images and fluoroscopic radiography images. The advantages are that complex fractures can be better visualized and that CT images can be taken before and after reduction. In addition, CT images present an entree for better intraoperative planning and model construction software, the surgeon visualizes the clinical situation, takes measurements, and plans the target location of implants and fixation screws for navigation. The plan is then saved for use during surgery. Shortly before surgery, the rolling cart with the display, computer unit, and tracking base unit is positioned in the operating room so that the surgeon can easily see the display. The position sensor is positioned so that it does not get in the way and its working area is roughly placed at the center of where the surgical actions will take place. The preoperative plan is loaded into the computer unit. The patient is then brought into the operating room and surgical preparations proceed as usual. Next, the surgeon validates the tool calibration and installs the dynamic reference frame with tracker mounting hardware. Before the beginning of surgery, the preoperative CT is registered to the actual intraoperative anatomic site with a CT registration procedure. Touching known anatomic landmarks with the tip of a surgical tool and verifying that the tool tip appears close to the landmark in the navigated image validates the registration. Once registration validation is successful, the navigated surgery begins. At key points during surgery, such as before drilling a pilot hole or inserting a fixation screw, one or more validation fluoroscopic radiography images are taken to verify that the navigated images correspond to the actual situation. The navigation procedure can be repeated with other tools and implants. At any time during the procedure, the navigation system can be stopped and the procedure can continue in a conventional manner. Figure 18-9 shows images of a typical CT-based navigation system. A key step in the protocol is the CT registration procedure. The relationship between the CT and the intraoperative situation is established by matching a set of points on the surface of the bone region to the corresponding points on the CT surface model. The intraoperative point set is obtained by touching the surface of the bone region of interest with a precalibrated tracked pointer and recording the location of a few dozen of these points by pressing on a foot pedal. The point set is then matched to a corresponding point set, automatically extracted from the CT surface model of the same bone region. The points must be a representative sample of the bone surface: that is, they must be as far apart as is possible and cover the entire region of interest.

Comparison of Fluoroscopy- and Computed Tomography-based Systems

Table 18-3 summarizes the advantages and disadvantages of navigation systems. Only CT-based systems allow for preoperative planning. Spatial visualization is only available with a CT data set and thus is only available in CT-based and 3D fluoroscopy-based systems. No additional registration procedure is necessary for intraoperative imaging, as the position sensor provides a common reference frame for trackers and images. All navigation systems require additional set-up procedures, which is a drawback as compared with conventional practice. CT-based systems are not suitable for fracture reduction, as there is no way to determine bone fragment locations during and after reduction. The 3D fluoroscopy-based systems can be used before and after, but not during, reduction, provided that both before and after, images are acquired. In fluoroscopy-based systems, reduction navigation is feasible when the bone fragments have trackers attached to them and new images are acquired at key points during reduction. Currently, CT-based navigation requires the surgeon to touch the surface of the bone; therefore, it cannot be used for percutaneous procedures. In terms of radiation, the best option for the patient and the surgeon is fluoroscopy-based navigation. The indications for fluoroscopy-based systems present the most options, while 3D fluoroscopy-based and CT-based systems are
best used with complex situations requiring spatial visualization. Currently, CT-based systems are mostly used for pelvic fracture fixation, while fluoroscopy-based systems are used for intramedullary nailing and fixation screw insertion.

**SURGICAL TECHNIQUES**

**Clinical Considerations**
The concept of combining computer-aided procedures in the treatment of trauma patients should take into account available innovative technologies together with the clinical situation, as part of the decision-making process. The main goals of CAS are less invasiveness and maximal accuracy in surgical procedures. It has been shown that, if used appropriately, this combination has added value. While the first generation of CAS uses computerized technology for current surgical concepts, it is clear that in the future the surgeon will be able to develop new ways of approaching surgical conditions.

There is no doubt that the timing and duration of procedures are of major concern in trauma management. Damage
control principles are considered the leading guidelines in the treatment of the severely injured patient. Alternatively, isolated skeletal trauma may be treated in a semielective fashion. Adding computer-assisted procedures to the trauma armamentarium is definitely influenced by, and affects, time-related factors. This is relevant to all stages of the trauma patients’ treatment, beginning with the preplanning stage and up to the end of the surgery itself.

Currently, most surgeons believe that CAS is a time-consuming, expensive, and cumbersome procedure. The system’s set-up time and registration process prolong the preplanning phase and might not suit acute trauma management considerations. Moreover, experienced surgeons believe that most surgical tasks can be easily, sufficiently, and accurately carried out, without the use of computer-related technologies. This conservative approach is well known in medical history, whenever a new technology emerges. For example, many years elapsed from the introduction of laparoscopic procedures until surgeons were ready to routinely use them.

Although computer-aided technology has been available for several years, it appears that we are still in the learning phase for CAS systems, and therefore, indications for their use are still being selected. Further assimilation of these promising technologies requires them to become easier to use (i.e., more user friendly). The set-up time for the computerized system will definitely be reduced in the modern surgical suite when it is built directly into the operating theatre environment, as presently available in several pioneering institutions. Furthermore, the execution of some surgical tasks is faster and more accurate with CAS equipment and will, in the future, allow for procedures that are presently considered almost unfeasible. For example, the placement of a sacroiliac screw in the fixation of pelvic and acetabular fractures becomes a fast and accurate procedure with minimal radiation by using a navigation system.

Retrograde percutaneous posterior column screw placement is an example of a procedure that previously had been considered an almost impossible task to perform and is now an available option with computer assistance. Robotic surgery may also play a role in this developing field. Robots are usually useful for several tasks; they offer precision and reproducibility, and are suitable for intensive labor and tedious and monotonous activities. Robots in the OR free the surgeon from such activities allowing him to concentrate on the surgery. Medical robots were introduced into the OR in the late 80s, followed by Robodoc (1992), an active robot for total hip arthroplasty. More recently, the da Vinci Surgical System (2003) was introduced for use in elective abdominal surgery and prostatectomy. Two modern commercial robots in orthopedics are the MAKO (2009) robot for hip and knee arthroplasty and Mazor Surgical Technology’s SpineAssist (2004) surgical robot, now called the Renaissance (2011), for spinal surgery, mainly pedicular localization for screw insertion and vertebral augmentation. Robotic technology has been used in spinal trauma and may, in the future, be useful in selected pelvic surgery. Several advantages were reported in robotic technology for spine surgery including: Between 50% and 70% reduced levels of radiation to the patient; reduced radiation exposure to the OR staff of 1,815 implants in 120 scoliotic adolescents; safety as illustrated in 593 cases with a 0.7% transient nerve deficit, as well as a short learning curve and simple integration into the OR flow.

The different CAS solutions including navigation, robotics, etc. may be categorized into “enablers” and “improvers.” While enablers refer to procedures that are not possible without CAS (i.e., the introduction of a new concept or ability rather than a

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**TABLE 18-3**

**Comparison between the Conventional Technique and Fluoroscopy-based and Computed Tomography (CT)-based Navigation Systems**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>No Computerized Navigation</th>
<th>Conventional Technique</th>
<th>Three-dimensional Fluoroscopy</th>
<th>CT-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preoperative planning</td>
<td>No (−)</td>
<td>No (−)</td>
<td>No (−)</td>
<td>Yes (+)</td>
</tr>
<tr>
<td>Three-dimensional views</td>
<td>No (−)</td>
<td>No (−)</td>
<td>Yes (+)</td>
<td>Yes (+)</td>
</tr>
<tr>
<td>Registration</td>
<td>No (+)</td>
<td>No (+)</td>
<td>No (+)</td>
<td>Yes (−)</td>
</tr>
<tr>
<td>Additional operating setup</td>
<td>None (+)</td>
<td>Yes (−)</td>
<td>Yes (−)</td>
<td>Yes (−)</td>
</tr>
<tr>
<td>Reduction</td>
<td>Yes (+)</td>
<td>Yes (+)</td>
<td>Limited (−)</td>
<td>No (−)</td>
</tr>
<tr>
<td>Percutaneous</td>
<td>Yes (+)</td>
<td>Yes (+)</td>
<td>Yes (−)</td>
<td>Yes (−)</td>
</tr>
<tr>
<td>Radiation to surgeon</td>
<td>Yes (−)</td>
<td>Very limited (+)</td>
<td>Very limited (+)</td>
<td>None (+)</td>
</tr>
<tr>
<td>Radiation to patient</td>
<td>Yes (−)</td>
<td>Very limited (+)</td>
<td>Yes (−)</td>
<td>Yes (−)</td>
</tr>
<tr>
<td>Indications</td>
<td>Current practice</td>
<td>Wide range of procedures</td>
<td>Complex anatomy</td>
<td>CT available; partially open</td>
</tr>
<tr>
<td>Current use</td>
<td>All of trauma</td>
<td>Intramedullary nailing; screw fixation</td>
<td>Just beginning</td>
<td>Pedicle screw insertion</td>
</tr>
</tbody>
</table>

+ an advantage; −, a disadvantage.
translation of a current technique into CAS), improves mainly yield improved accuracy and not a new concept. A simple but extremely important example of improvement is the significant reduction in radiation exposure that can be achieved with CAS. 23 As more orthopedic procedures are found to be suitable for CAS applications and as younger surgeons, born into the era of information technologies, enter the operating theatre, the adoption of CAS will become more natural and routine in the operating room.

Currently the simple indications for using CAOS–ST systems in trauma care are percutaneous surgical procedures in which added imaging can provide essential information that will contribute to reducing invasiveness and increasing accuracy. 24 Clearly, the fixation of nondisplaced fractures is most suitably carried out with navigation systems, although often the indication for internal fixation is questionable. Alternatively, because available systems can only follow one or two tracked bony fragments, they are not suitable for treating displaced multiple fragment fractures such as comminuted articular fractures, where careful anatomic reduction is required.

In general, navigation systems function better in static or stable situations. For example, using a fracture reduction table or an external fixator eliminates movement between fragments and creates a temporary situation in which there is little or no movement at the fracture site. Moreover, it has been shown that in such “stable” situations, the reference frame can be attached to the fracture table, avoiding additional harm to the patient, while maintaining acceptable accuracy. 25 Following fracture reduction, a guidewire or fixation tool can be inserted using the navigation system according to specific clinical guidelines.

Required accuracy is a key factor for deciding whether to use a CAOS–ST system. For example, the accuracy needed for pedicle screw insertion is far greater than that needed for hip fracture fixation with cannulated screws. Required accuracy is directly influenced by the cost of inaccuracy (e.g., the cost of inaccuracy in spinal surgery is much greater than in intramedullary nailing).

Computerized navigation has been shown to increase placement accuracy and reduce variability as compared with manual placement. The accuracy of computerized navigation in cannulated screw placement in hip fracture fixation was evaluated. 2 After verifying stable reduction on a fracture table, the reference tracker was attached to the anterior superior iliac crest. The reference frame was not attached to the affected bone so as to improve working convenience during the procedure and minimize morbidity. It was found that the accuracy of the procedure was much better than that of conventional manual procedures. The navigation system enabled the surgeon to place screws with optimal alignment including configuration, parallelism, and scattering. This experience demonstrates that stable reduction creates an acceptable situation for navigational systems and that the reference-tracked frame may be fixed, on such occasions, to an adjacent bone as well as to an external fixator or to the operating table, as mentioned earlier. 3

**Preparation for Surgery**

Before surgery, the decision as to whether the procedure is suitable for CAOS–ST is determined by the surgeon’s knowledge and capabilities. In most trauma cases, fluoroscopy-based navigation (2D or 3D) is the method of choice.

It is very important to plan and prepare the operating room to create a surgeon-friendly environment and to enable proper tracking without interference (Fig. 18-10). Adding CAOS–ST equipment (computer, monitor, position sensor, and trackers) to an already crowded room requires careful planning. The computer screen should be positioned so that the surgeon can see it without any effort, because, as in arthroscopic procedures, most of the time the surgeon will watch the screen rather than the operative site. Easy access to the computer’s control panel is also important and is usually realized with a sterile touch screen. When using optical tracking, maintaining an unobstructed line of sight between the position sensor and the trackers is very important. Thus, the location of the position sensor with respect to the surgeon, nurses, and patient must be carefully examined. These ergonometic issues will definitely be easier in newly designed operating rooms in which computer screens and modern remote controls will be built-in.

Inherent to the implementation of a new technique is the learning curve. In CAS, the learning curve affects all members of the surgical team. It affects surgeons performing the operation, nurses having to cope with new tools, anesthetists who need to adjust the anesthesia time to the expected operation time, and x-ray technicians who sometimes need to operate fluoroscopy-based navigation. The entire team should be aware that there is a “new partner” in the operating theater (i.e., the computer), and sometimes a computer technician will also need to be part of the surgical team.

During the initial phase, the minimal required free field of vision is determined by the location of the C-arm and the calibrating targeting device, the reference frame tracker attached to the patient’s anatomy, and by the optical camera. The calibrating targeting device is typically a ring tracker attached to the fluoroscope or the newly designed hands-free trackers that overcome the obstacle of attachment of the cumbersome targeting device to the C-arm. During the navigation phase, tracked surgical instruments replace the ring tracker and the tracking space changes accordingly. Continuous tracking of the patient’s anatomy and of the surgical instrument is required. Verification and validation are extremely important at every stage in order to achieve optimal accuracy. Tracking the surgical instrument is more simple and precise, whereas tracking the anatomy, especially in trauma surgery, is more problematic, particularly in those cases where two fragments are simultaneously tracked, as in the fracture reduction process.

Registration and tracking of the patient’s anatomy are usually the main cause of inaccuracy. The first obstacle is attaching the rigid frame to the patient. The problem of inserting a stable screw into the bone fragment is well known from the use of external fixation. Screw or pin grip depends on their design and on bone quality. For each procedure, the location needs to be selected according to local morbidity (soft tissue access and crucial anatomic structures); convenience during the procedure (line of sight and free surgical site); and stability of anatomic frame fixation. The stability of the screw holding
the anatomically referenced tracked frames depends on bone quality and soft tissue interference. Subcutaneous locations such as the iliac crest or the medial aspect of the tibia are preferable. The site of frame fixation should also take into account the surgical task (e.g., avoiding the medullary canal in intramedullary long bone fracture reduction).

Newly designed frames contain more than one screw as well as several soft tissue adaptors and are able to detach from the frame during the non-navigational steps of the procedure. Improvements in bone tracking technology, as well as the ability to track more than one or two large bone fragments, significantly enhance the surgeon’s surgical performance in the treatment of fractures.

**Basic Procedures Under Navigation**

The clinical situations in which computerized navigation is recommended will be presented. For each clinical application, both the rationale and the contribution of these systems will be discussed. The aim of this section is to expose the reader to the first generation of computerized navigation systems. The specific indication for each surgical procedure is beyond the scope of this discussion. All the surgical navigation procedures discussed are based on optical infrared tracking.

When using fluoroscopy-based navigation, the first step is to mount the ring tracker on the C-arm and drape it for sterility. The optimal images are stored in the computer and activated during the navigation process. It should be noted that, for all of the clinical examples to be discussed, the preliminary fluoroscopic views can be taken while the operating team stands at a distance of 2 m or more from the radiation source, thus almost eliminating the team’s radiation exposure.

The next stage relates to the activation of the designated surgical tool (i.e., wires, awls, drill bits, etc.) or the actual implant, which is to be attached to a tracker, commonly referred to as the instrument tracker. The contour of the instrument in its current location is displayed on the previously activated fluoroscopic images thereby creating the effect of virtual fluoroscopy. Similar concepts may be used for tracking fracture reduction—in this case, instead of following the relationship between the tracked instrument and the tracked bone, we track the relationship between the two tracked bone fragments (Fig. 18-11).

Currently available procedures are as follows.

- Trajectory navigation—drill guide applications (hip and pelvic fractures)
- Fracture reduction
- Intra-articular fracture fixation
- Novel uses of navigation: Localization of bone lesions or removal of surgical hardware and shrapnel

### Trajectory Navigation—Drill Guide Applications (Hip and Pelvic Fractures)

Insertion of straight surgical fixation implants such as nails and screws is a common task in orthopedic traumatology. This procedure can often be performed percutaneously and thereby fit the CAS philosophy of minimal invasiveness with high accuracy. Navigated 2D fluoroscopy provides a natural computerized enhancement for this surgical application. Thus, the most common current indication for the use of CAOS–ST systems is the insertion of cannulated screws. This surgical procedure requires high accuracy and unusually large radiation exposure for the surgeon and for the patient. Both issues can be successfully addressed with fluoroscopy-based navigation.

The percutaneous treatment of pelvic and acetabular fractures and internal fixation of slipped capital femoral epiphysis are procedures that can greatly benefit from computerized navigation. The use of computerized navigation turns the procedure into a simple task to perform, while using minimal radiation. Internal fixation of intracapsular fractures of the femoral neck is considered straightforward, although accurate performance requires high proficiency on the one hand and large exposure to radiation on the other. A prospective comparison between patients who underwent internal fixation of intracapsular fracture of the femoral neck by means of cannulated screws, with and without the assistance of a navigation system, was performed. This study revealed that computerized navigation increased the accuracy of screw placements in all measured parameters. Having acquired proficiency with the computerized system, the surgeon is ready to move on to the next level, which includes percutaneous fixation of pelvic and acetabular fractures.

Internal pelvic fracture fixation is a challenging task for the orthopedic trauma surgeon. The pelvis is a complex 3D structure that contains important anatomic structures in a confined environment. Therefore, surgical fixation of displaced fractures...
FIGURE 18-12 Cannulated screws. A: Anteroposterior and lateral views of a reduced intracapsular fracture of the femoral neck displayed on the computer’s screen. B–D: Insertion of the three guidewires without additional radiation. E, F: Radiograph and CT scan showing the precise scattering of the three screws in a spatial configuration of an inverted triangle. (Images property of authors.)
should be meticulously performed under strict visual control, because the “safe zones” are narrow. With CAS technologies, it is possible to define several “safe corridors” for the insertion of different screws around the pelvis including the acetabulum. It has been shown that navigation is advantageous for these challenging procedures.\(^{36-38}\) 

In many cases, closed reduction and percutaneous fixation is feasible and provides enough stability to allow for immediate patient mobilization. A conventional image intensifier is most frequently used in percutaneous pelvic fixation. However, it provides only a 2D image and requires multiple images in different projections to determine the correct point of entry and the direction of the screw. Furthermore, the use of conventional fluoroscopy makes the procedure long and tedious and exposes both the patient and the medical team to prolonged radiation.\(^{16,19,29-31}\) Fluoroscopy-based navigation systems (2D and 3D) have the potential to significantly reduce radiation exposure and operative time, while allowing the surgeon to achieve maximum accuracy.\(^{36,26,29-33}\)

The indications for percutaneous pelvic and acetabular surgery are controversial and are not discussed here. A selected population with traumatic pelvic and acetabular fractures can be treated percutaneously under three conditions: (i) cases with minimally displaced pelvic and acetabular fractures; (ii) displaced fractures where closed reduction is feasible; and (iii) in cases of open pelvic surgery when the insertion of several screws is very challenging and demands the assistance of guiding systems such as fluoroscopy or navigated fluoroscopy following appropriate open reduction.

It is important to note that the percutaneous approach to fracture fixation of the pelvis continues to evolve and undergo many improvements and developments in which computerized technology may be of great assistance. For example, in preplanning, the use of standard axial CT data to create computer-reconstructed 3D images and/or models may replace the standard radiographic assessment of pelvic and acetabular fractures.\(^{30,32-35}\) Similarly, 3D fluoroscopy technology allows the surgeon to obtain immediate and accurate 3D reconstructions in the operating room. By integrating these images into navigation systems, preplanning becomes easier and more accurate and allows for direct, truly spatial surgical navigation. It also enables the precise evaluation of closed reduction (using a fracture table, external fixator, and/or other fixation instruments) before insertion of the navigated screws.

**Surgical Technique**

For both acetabular and pelvic surgery, the dynamic reference frame can be rigidly attached to the patient’s iliac crest. Several appropriate fluoroscopic images of the pelvis are acquired and saved in the system’s computer. No further fluoroscopic imaging is necessary, except for verification fluoroscopy prior to the insertion of the cannulated screw, or in the case of reduced fracture, the crossing of the fracture site.

During surgery, following the activation of the fluoroscopic images, the surgeon can accurately determine the entry point and direction of each screw. At the same time, by means of a virtual trajectory line, the correct length and diameter of the screw can be calculated (Fig. 18-12). After satisfactory virtual alignment and length have been achieved, the conventional guidewire pertaining to the cannulated screw system is driven through the drill guide. Before insertion of a self-drilled cannulated screw, the position of the guidewire should be verified by fluoroscopy. When the insertion of several screws in the same area is required, such as in the fixation of fractures or dislocations in the sacroiliac zone, the acquired fluoroscopic views can be used for the insertion of more than one screw (Figs. 18-13 and 18-14).

In pelvic surgery, serious complications can arise from the surgical procedure and intervention, rather than from the initial injury. Therefore, it is only natural that percutaneous minimal surgical approaches are sought to overcome the difficulties that arise in relation to fractures in the complex anatomy of the pelvis and acetabulum. Figure 18-9 illustrates the placement of a retrograde anterior column screw using a CT-based navigation system.

**Fracture Reduction**

Intramedullary nailing is the preferred surgical option in many long bone fractures. Although it is a routine procedure, performed by most trauma surgeons, it is not devoid of technical pitfalls and complications. Achieving accurate and successful results with conventional techniques involves exposure to significant amounts of radiation for both patients and the surgical team.

Fluoroscopy-based navigation can be helpful in closed intramedullary nailing by increasing precision, minimizing soft tissue damage, and significantly decreasing radiation exposure.\(^{36-38}\) Several surgical goals can be achieved by using computerized navigation systems. The insertion of instruments based on real-time information becomes possible and significantly increases the accuracy of nail placement. Determining the exact point of entry of the nail is critical because it is one of the main sources of morbidity in intramedullary nailing as well as a cause of misalignment. As previously discussed, computerized navigation systems help to precisely locate the nail entry point by means of trajectory navigation, thus minimizing soft tissue dissection. This is particularly helpful in special cases such as in obese patients where anatomic landmarks are obscured. Working with several images simultaneously can also decrease unnecessary drill holes, tissue damage, and cartilage perforation, because all targeting is done virtually, prior to the introduction of the actual instrument. The insertion of locking screws into certain nails can be a potential hazard for neurovascular structures.\(^{22,38,39}\) Additional improvement in nailing techniques is achieved by the facilitation of Poller screw insertion. When precisely placed, better angular correction of metaphyseal fractures is achieved. Another important future contribution of the new generation of navigation technology will be to allow for the tracking and aligning of two fragments, thus enabling fracture reduction without radiation and reduction wire insertion, and perhaps most critically, its ability to provide the surgeon with accurate information to restore alignment, including length and rotation.\(^{31,38,40}\) The precision of length measurement may also decrease the rate of complications associated with nailing such as protrusion of the nail or screw ends.\(^{41-43}\)
**Surgical Technique**

A fluoroscopy-based surgical navigation system can be used, either for the entire operation, or for different stages of intramedullary nailing. These include the nail’s entry point, nail and screw measurements, freehand locking, placement of auxiliary screws, as well as fracture reduction and the assessment of length and rotation. Navigation of the entrance point and the locking procedure are performed by using straight line trajectory. The reference frame should be attached to the tracked bone fragment, either proximal or distal, depending on the specific task.
FIGURE 18-14 Sacroiliac and pubic ramus screw. 
A–C: An intraoperative display of the computer screen during insertion of a sacroiliac screw and two intramedullary pubic ramus screws.  
D, E: Inlet and outlet postoperative verification radiographs showing the accurate real placement of the three screws. (Images property of authors.)
1. **Nail entry point**: The actual point of entry is determined by the use of simultaneous virtual fluoroscopic views, usually anteroposterior (AP) and lateral views. Before incision, the tracked drill guide is drawn next to the skin. Its position is adjusted by viewing its virtual trajectory superimposed on the activated fluoroscopic images so as to minimize the surgical exposure. The entry point location is established while moving the tracked drill guide to an optimal position (Fig. 18-15A). No further fluoroscopy is required and a verification fluoroscopic image is taken only after insertion of the guidewire. After this task is performed a cannulated awl or a larger cannulated drill is inserted, according to the manufacturer’s instructions, through this guide to open the medullary canal.

2. **Freehand locking**: This technique is relatively easy to perform and involves minimal radiation exposure. The bone tracker is fixed close to the location of the locking screws. Using the “perfect circle” technique, an AP or lateral view of the locking hole, in which the holes almost resemble circles, is obtained. An additional AP or lateral view may be taken to determine the screw length. The tracked drill guide is then drawn toward the locking screw area and is navigated until a circle appears within the hole on the computer screen (Figs. 18-15B, C). This is followed by drilling through the tracked drill guide and inserting the locking screw. Sometimes, such as with tibial nailing, the same AP and lateral views can be used for insertion of two or even three adjacent locking screws. New advanced technologies are designed to facilitate easy locking with less radiation than conventional navigation.

3. **Placement of other screws**: Poller screws are important tools for correcting bone alignment when nailing metaphyseal fractures. Precise placement of these screws can now be performed using a technique similar to that of locking screws. Virtual fluoroscopy based on AP and lateral images enables easy and precise positioning of Poller screws. For “miss-a-nail” screws, additional AP and lateral images of the proximal femur are obtained following the insertion of the intramedullary nail. The goal is to insert the cross-neck screw without interfering with the intramedullary nail. The navigation system enables the surgeon to determine the precise position of the “miss-a-nail” cross-neck screws and to safely navigate through the narrow safe zone (Fig. 18-16).

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**FIGURE 18-15** Intra medullary nailing. **A:** Typical computer display used during antegrade femoral intramedullary nailing consisting of simultaneous anteroposterior and lateral views, where the pink line represents the guide’s insertion point at the precise entry point in the piriformis fossa and the green line represents the nail’s direction. **B, C:** Proximal locking hole in the retrograde femoral nail. Note the hole as a perfect circle enabling precise aiming of the locking screw. (Images property of authors.)
FIGURE 18-16 Intramedullary nailing: Poller and “miss-a-nail.”
A: Poller screw planning for reduction of a proximal tibial fracture. The red circle depicts the planned position of the Poller screw. The green line is the virtual nail. The surgeon can predict the relationship between the two. B, C: Poller screw insertion process. D, E: “Miss-a-nail” screw through a femoral neck fracture after insertion of a femoral nail with a spiral blade. D: Planning the “miss-a-nail” route with the navigation system displayed as a green line. E: Fluoroscopic image after nail insertion. Note the parallelism between the planned and real route of the nail. (Images property of authors.)
4. Fracture reduction: New software is available for the entire fracture reduction procedure. This became possible because of the ability to simultaneously track two reference frames. The frames are attached to the distal and proximal long bone fragments. Several AP and lateral views are acquired, enabling visualization of the entire bone. Usually, six views (three AP and three lateral) are needed to visualize the proximal fragment, the fracture site, and the distal fragment in two planes. It is possible to virtually define each segment on the computer display and to track each fragment by navigation as already described. The special location of each fragment in relationship to the other enables actual fracture reduction and insertion of the reduction wire. The procedure resembles the fluoroscopic process of fracture reduction surgery with two major advantages: No radiation and simultaneous two-plane tracking. The ability to track and visualize the entire bone enables the taking of several measurements including length and rotation. Newly computerized navigation software provides accurate measurements of length and rotation (Brainlab navigation, Brainlab Trauma 3D). It enables access to biomechanical data of the nonfractured side for reproduction on the fractured side. A noninvasive optical tracker is placed on the uninjured thigh at the beginning of the case, using a Velcro strap. Tracked AP and lateral images of the proximal and distal femur are obtained. A handheld tracker placed in the vicinity of a C-arm fluoroscope (X-Spot) is used to track and register the images along with the noninvasive tracking. The resultant images are marked by the surgeon on four landmarks: The center of the femoral head; the tip of the greater trochanter; the most posterior part of the femoral condyle; and in the center of the knee. The software automatically calculates the axial rotation angle between the proximal and distal femoral landmarks as well as the femoral length and stores the values for later reproduction. The injured extremity is then prepped and the femoral nailing procedure commences in a standard surgical fashion according to the surgeon’s preference. Following nail insertion and prior to any nail interlocking, trackers are placed both proximally and distally to the injured femur and an identical process of imaging acquisition and landmarking, as described above for the uninjured extremity, is repeated. At this point, the tracking camera of the navigation system records the length and rotation of the injured nail. The rotation and length is corrected, followed by interlocking screw placement to secure the alignment. Preliminary data indicate that this technology is feasible in the clinical set-up and may significantly contribute to the clinical outcome of long bone fracture reduction (Fig. 18-17). Recently, several software packages have been developed that also enable the tracking of implants, particularly plates. Thus, it is possible to track the position of the implant in relationship to the bone. This technique overcomes some of the drawbacks of the first generation of computer navigation systems. In the future, customized tracked instruments based on these principles will further improve and facilitate computer-aided intramedullary nailing.

Intra-articular Fracture Fixation

Intra-articular fracture fixation presents unique technical difficulties. In many cases, the fracture is comminuted and has complex geometry that is difficult to evaluate on conventional CT slices or fluoroscopic radiography images. Recently introduced 3D intraoperative imaging, such as Iso C-arm imaging, is a useful tool for this visualization. However, it too has limitations. It can be used only once or twice during surgery because of radiation exposure and it is a static view. Other difficulties include tracking of small bone fragments and possible fragment motion during fixation.

Intraoperative Control

Intraoperative, rather than postoperative, confirmation of the reduction and fixation of intra-articular fractures can save patients and surgeons from uncertainty relating to the quality of the reduction. Recent developments have yielded new options for intraoperative 3D imaging. The SireMobil Iso-C 3D (Siemens Medical Solutions), for example, combines the capabilities of routine intraoperative C-arm fluoroscopy with resultant 3D images. The 3D imaging equipment has the ability to automatically revolve around a fixed surgical target (isocentric) acquiring up to 100 images. Of these images, axial cuts and 2D and 3D reformations can be generated which are comparable to CT images. Using this unique imaging modality can help the surgeon to intraoperatively assess not only the fracture anatomy, but also the position and configuration of the implants in correlation to the area of surgery, including those in the vicinity of the acetabulum and the posterior pelvic ring. The performance of the Iso-C 3D has already been described in several studies for intraoperative demonstration of high-contrast skeletal objects, with encouraging results. The persisting disadvantages of 3D fluoroscopes are their limited image size of 12.5 cm, which is sufficient for the sacroiliac joint but not for the entire posterior pelvic ring, and their relatively inferior image quality. Modifications of the isocentric C-arm have recently been introduced, offering superior image quality, increased field of view, higher spatial resolution, and soft tissue visibility, as well as the elimination of the need to rotate around a fixed point (isocentricity). In addition, newly developed patented software modules have recently been developed which allow for intraoperative 3D assessment, with decreased cost and less radiation, using conventional fluoroscope techniques.

Fracture Fixation

An improved method for image guidance in intra-articular fracture fixation is 3D fluoroscopy-based navigation. Of the intraoperative axial cuts, 2D and 3D reformations can be generated and the data can be transferred to the navigation system. With inherent registration, the navigation procedure can be performed, similar to CT navigation, but without any registration procedure. New developments integrating a second-generation 3D fluoroscope (e.g., the ARCADIS OrbiC; Siemens AG, Erlangen, Germany; O-arm Surgical Imaging System; Metronic, Minneapolis, MN, USA) and a multifunctional navigation system onto one common trolley markedly improve data transfer and
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system handling. Thus, the indications for image guidance in intra-articular fractures, including pelvic surgery, have expanded in order to reduce open procedures (Fig. 18-18). The increasing use of these new technologies provides intraoperative control, thus facilitating their use in trauma surgery of the spine.28,58,59

Novel Uses of Navigation: Localization of Bone Lesions or Removal of Surgical Hardware and Shrapnel

The simplest indication for using CAOS–ST systems is a situation in which a foreign body is retained in bone or soft tissue, such as surgical hardware or penetrating injuries with retained metals (e.g., shrapnel, nuts, and bolts), that need to be removed. It is not necessary to track foreign bodies, as they usually remain in place and do not drift. They can be reached with a navigated tool by following the tool’s location with respect to the foreign body in the activated fluoroscopic images. Given the simplicity of the procedure, we recommend that this be the first surgical procedure using computerized navigation systems to be performed by inexperienced surgeons.2,60,61

The main indication for metal/hardware removal is local discomfort, although other indications include infection or risk of

FIGURE 18-17 (continued) C: Acquisition of fluoroscopic images of the treated side with two reference frames attached to the distal and proximal fragments using a new image registration method that has been introduced consisting of a portable device “Expot” that is not connected to the fluoroscope and includes trackers and markers that allow for an easy registration process. D: Definition of the same anatomical landmarks on the treated side, not the rigidity attached reference frame. E: Navigation of entry point. E1: Clinical. E2: Display image.
toxicity. The removal of missiles retained in an inaccessible location poses a major problem for the trauma surgeon because they can be hazardous to the integrity of adjacent internal structures.

Fluoroscopy-based navigation is the method of choice for these situations. Unlike CT-based systems, it requires very short preoperative preparation, making it appropriate in emergency situations as well, where its effectiveness has already been proven even during the urgent stages of treatment. Thanks to the high accuracy of fluoroscopy-based navigation, its use in complex and dangerous situations where a foreign body is located in the proximity of structures such as blood vessels and/or nerves is promising. In comparison to other conventional techniques, the use of fluoroscopy-based navigation has allowed orthopedic surgeons to minimize soft tissue dissection. The same principle can be used for guided bone biopsy.

**Surgical Technique**

Tracked reference frames are rigidly attached to the patient’s adjacent bone and to a calibrated pointer. Several fluoroscopic images of the required anatomic site are acquired and stored in the computer, or 3D information using Iso-C technology is acquired. The accurate spatial location of the foreign object can be seen in the images displayed on the computer’s screen (Fig. 18-18). The surgeon then plans the most accurate and safest minimal surgical approach for the foreign body that needs to be removed. Once the stored fluoroscopic images have been activated, the location of the guided probe with respect to the patient’s anatomy is continuously displayed and updated on all of the fluoroscopic images. This enables accurate determination of the entry point and spatial advancement of the probe toward the foreign body.
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COMPLICATIONS AND CONTROVERSIES

The most frequent clinical and technical complications that lead to navigation errors and failure are listed.

1. Loss of line of sight

An unobstructed view between the optical camera and the trackers at all times is the basic requirement of optical navigation. Loss of line of sight occurs when the view between the optical camera and one or more of the trackers is obstructed by the surgeon or another member of the surgical team, the patient’s body, the fluoroscopy C-arm, the overhead lamps, or any other object in the vicinity of the surgical field. When there is no line of sight, the tracker, which is not seen, either disappears from the display or the entire display freezes. Navigation resumes as soon as the obstruction disappears.

Loss of line of sight can be remedied by moving the object causing the interference, by repositioning the optical camera, or by changing the surgical team’s location around the patient. In some situations, because of the surgical approach, it is not possible to see all of the trackers at once. In this case, partial navigation is possible with the visible trackers. In some surgical situations, maintenance of the line of sight is not possible and therefore navigation should be avoided. As previously discussed, the surgeon can control some of the obstacles by appropriate placement of the trackers and the camera. In practical terms the availability of line of sight should be considered as an integral part of the preplanning stage of CAOS–ST.

2. Shift of the dynamic reference frame rigid bone mounting

Maintaining a rigid attachment between the bone tracker and the bone throughout surgery is essential in order to guarantee registration accuracy. Shifting is usually the result of bone fixation loosening, poor jig fixation, or unintentionally pushing or hitting the tracker and its mounting jig. An undetected shift will result in inaccurate navigation images that might mislead the surgeon and lead to undesired results and complications. To avoid this situation, the surgeon should ensure that the tracker mounting jig is securely fixated to the bone structure.

The only way to detect dynamic reference frame motion is by validation. Validation is performed either by acquiring one or more fluoroscopic radiography images and comparing them with the navigation images, or by using the tip of a surgical tool to touch known anatomic landmarks and verifying that the tool tip appears close to the landmark in the navigated image. Validation should be performed at key points during surgery and always when in doubt.

3. Tool decalibration

Tool decalibration occurs when the geometric data of the tracked tool does not match its actual geometry. Tool decalibration is caused by tool wear and tear (e.g., tip bending, frame deformation because of repeated sterilization or tool tracker shift). To avoid these situations, the surgeon should verify tool calibration before surgery, at key points during the surgery, and always when in doubt. Tool decalibration cannot be detected automatically. The surgeon must perform a tool calibration verification procedure, which usually involves the use of custom calibration software and hardware.

4. Navigation image inaccuracy

Inaccuracy of navigation images is the mismatch between the displayed images and the intraoperative situation. Inaccuracy is the result of errors in the registration chain. The main causes of the errors include the shift of the dynamic reference frame, tool decalibration, and the shift of the...
C-arm tracker ring. Secondary causes include tracking system drift over time and navigation at the edge of the position sensor working volume. Other causes are related to the images themselves. In CT images, they include poor contrast, low slice resolution, insufficient radiation dose, large spacing between slices, patient motion during the CT scan, and blooming artifacts as a result of the presence of metallic objects. In fluoroscopic radiography images, they include poor image resolution, poor contrast because of insufficient or excessive radiation, inappropriate viewpoints, and patient motion during image acquisition.

The surgeon must realize that the acquired images serve as the basis for the entire navigated surgical procedure. Therefore, optimization of these images (contrast, field, viewing angle, etc.) is crucial and should be done during the image acquisition stage, before surgery begins. Note that navigation image inaccuracy can be observed by the surgeon but cannot automatically be detected. It requires performing validation tests for C-arm ring and dynamic reference frame shift, tool decalibration, restarting of the tracking system, repositioning of the position sensor, and the acquisition of new images.

FIGURE 18-19 Shrapnel removal. A: Preoperative computed tomography scan showing shrapnel that needs to be removed because of its proximity to the left hip joint. B: Four acquired images displayed on the system’s screen, showing the location of the missile and allowing for immediate presurgical planning of the percutaneous surgical approach. The pink line represents the surgical tool and the virtual green line assists in determining the point of entry and direction of the surgical tool. C: The surgical tool, represented by the pink line, arrives at the missile. D: Verification fluoroscopy followed by removal of the missile. (Images property of authors.)
5. System robustness issues

Robustness is the ability of a system to perform its intended tasks with a minimum number of failures over time. The more robust the system, the more acceptable it will be to the surgeon. Robustness depends on both software and hardware components. Software failures include flaws in the computer operating system, in the custom-designed software, and in the tracking base unit controller. At best, software flaws can be temporarily overcome by restarting the system. At worst, they require pre-emtping navigation and reporting the flaw to the company. Hardware failures include failure of the computer unit, poor cable connections, and failure of the tracking unit.

6. Verification of surgical tool and implant spatial position

The surgeon should always remember to make a distinction between the virtual and nonvirtual situations displayed on the computer screen. This is of great importance in trauma surgery because the surgeon is used to working under fluoroscopic guidance that provides a true view of the surgical site as opposed to the virtual display in CAOS–ST procedures. For example, a perfect virtual position of a guidewire may be a false presentation of the real situation, because during insertion of the real guidewire, it may slip or bend and point to a wrong position, without being detected or shown on the augmented image. There are several ways to tackle this critical obstacle. The best is to use rigid guidewires to prevent bending so as to penetrate the cortical bone in the right location. Experience and/or the use of rigid drills can usually overcome this problem. In addition, it is also very important to perform real-time fluoroscopic verification at critical or questionable time points during the surgical procedure.

7. Adaptation to different surgical techniques

The main addition to computer-assisted navigation compared with conventional fluoroscopic trauma surgery is the bone-mounted reference frame. The significant ramifications of the loosening of the reference frame have been previously described. The actual location of the frame can interfere with the surgical procedure. For example, while inserting the reference frame screw into the bone diaphysis during intramedullary nailing, it should not obstruct nail passage within the medullary canal. In addition, during the insertion of a locking screw, the reference frame might be in the way and prevent either an accurate line of sight or the proper positioning of certain surgical instruments (e.g., drills). The surgeon must choose between placing the frame close to the operative site, to increase the accuracy of the procedure and to improve triangulation, and placing the frame where it establishes a convenient working distance.

PERSPECTIVES

Technical and Economic Perspectives

Navigation systems are limited by technical elements. Currently, their main limitations, in decreasing order of importance, and perspectives for improvements are as follows.

1. Support for implants and instrumentation

Navigation systems are designed to be used with specific tools, implants, and hardware from specific manufacturers. The choice of supported instruments and implants depends on decisions made by the navigation and instrument companies, which are primarily dictated by commercial interests. Often, the software module only accepts models from one manufacturer. In some cases, tools from other manufacturers can be incorporated following a tool calibration procedure. Currently, only a handful of instruments and implants are supported.

2. Support for surgical procedures

Navigation systems require software modules (software surgical protocols) that implement the surgical protocol for navigation for specific procedures. Without the custom software module for the surgical procedure, the navigation system cannot be used, although in principle it is technically feasible in procedures other than those for which they were designed. Currently, only a handful of procedures are supported.

3. Improvements in tracking technology

Current optical tracking technology has several drawbacks, including line of sight, size of trackers, cables, number of trackers, accuracy, and cost. Magnetic tracking offers a variety of potential advantages, including no line of sight requirement, reduced tracker size, and reduced cost. Although the technology is not as yet ready for routine clinical use, it is likely that some of the obstacles will be overcome in the near future, offering the possibility of tracking bone fragments and easing tracker fixation to the bone, thus significantly reducing or eliminating dynamic reference frame shift and opening the door for navigation during reduction.

4. Image-based CT registration

Current CT-based navigation systems require the surgeon to acquire points on the surface of the anatomy of interest to perform the registration between the CT data set and the intraoperative situation. This precludes its use in percutaneous procedures because it is time consuming and error prone and produces suboptimal registration results. An alternative is to use fluoroscopic radiography images instead of points harvested from the bone surface. This type of registration, called anatomy-based CT to fluoroscopic radiography registration, has been demonstrated in the laboratory and will soon be available in navigation systems.

5. Planning

Current intraoperative planning is either nonexistent or limited at best. Intraoperative definition of goals, such as screw path safety zone and insertion axis, can greatly help the surgeon perform the surgery. The blurring of the distinction between preoperative and intraoperative planning opens the door for better, more adaptive planning and consequently better and more consistent results.

6. Spatial visualization without CT

A drawback of fluoroscopy-based navigation systems is that they do not show spatial views of the intraoperative
situation, which can only be produced when CT data are available. Isometric fluoroscopic technology (Iso-C) overcomes this obstacle; however, it provides a relatively small visual field. Newly designed technology is now available with better quality and a larger view. Another way to overcome this limitation has been proposed—to acquire several fluoroscopic radiography images and adapt a closely related CT or generic anatomic model so as to match the patient-specific fluoroscopic radiography images. This approach, called atlas-based matching, is currently under investigation.

7. Ergonomic factors
Most operating rooms were not designed with new technology in mind in terms of size; placement of the computer, computer screen, and cables, etc. A surgeon experienced with CAS can appreciate the advanced ease of use in newer generations of navigation systems. However, the insertion of a navigation system into the operating room still warrants special consideration. The machine occupies space. Its positioning is dictated by line of sight between the tracker sensor and the markers.

These obvious technical and economic factors need to be taken into account along with the human factors.

Clinical Perspectives
The use of computerized navigation systems in orthopedic trauma surgery is rather new. The four main contributions to trauma surgery are as follows.
1. They facilitate less invasive surgery by reducing soft tissue damage, thus shortening the postoperative rehabilitation process.
2. They improve the accuracy of fracture reduction and implant placement compared with that obtained with conventional methods and reduce the outcome variability.
3. They significantly reduce radiation exposure to both the patient and the surgeon.
4. They create a powerful educational and quality control tool.

Most of the contributions achieved to date are in the preplanning stage. For example, if we look at the imaging field, it is clear that computerized imaging supplies a better 3D understanding that may influence the planning of the surgical procedure. Undoubtedly, this technology can, and should, change our way of thinking in relation to other stages of surgical treatment.

It is quite obvious that computerized navigation systems are continuously advancing and offer additional possibilities. Although these systems are still in their infancy, it appears that they have already managed to change the setting in several trauma centers. The CT suite can be transformed into an operating room or, alternatively, the modern hi-tech fluoroscope can now be altered to produce 3D images. These technologies together with surgeons’ preferences and compliance will in the future determine the set-up of the operating room. Future generations of computerized navigation systems will be characterized not only by improved accuracy but also by improvements to robustness and improving working convenience in the computerized environment. When these changes finally take place, it is expected that computerized technology will be of assistance not only in navigation but also in the execution of the surgical procedure by means of robots. If the trauma surgeon can overcome the difficulties entailed in integrating the new technology, we may experience a revolution in surgical approaches and education.

GLOSSARY
General
CAOS (computer-aided orthopedic surgery). Planning and execution of orthopedic surgery with the help of a computer system.
CAOS–ST (computer-aided orthopedic surgery in skeletal trauma). Planning and execution of orthopedic trauma surgery with the help of a computer system.
CAS (computer-aided surgery). Planning and execution of orthopedic surgery with the help of a computer system. Synonyms: Computer-assisted surgery, computer-integrated surgery (CIS), image-guided surgery (IGS), surgical navigation.

Planning
Model. Computer representation of the relevant characteristics (e.g., shape, location, main axis) of an object of interest (e.g., a bone, bone fragment, surgical instrument, implant, fixation plate, cutting plane). Synonym: Digital template.
Preoperative planning. Process of creating a computerized plan for the purposes of surgery.
Surface mesh. Geometric description of a bone surface consisting of a collection of interconnected points, usually extracted from CT data. Synonym: Surface model.

Navigation
CT-based navigation. Navigation with images created by superimposing onto a preoperative CT cross section and spatial images the surgical tool silhouette and updating its location in real time.
Fluoroscopy-based navigation. Navigation using images created by superimposing onto conventional fluoroscopic images the surgical tool silhouette and updating its location in real time, thereby creating the impression of continuous fluoroscopy without the ensuing radiation. Synonyms: Virtual fluoroscopy, augmented fluoroscopy.
Guidance. Process of indicating in real time to the surgeon, via images, graphics, or sound, the best course of action during surgery.
Navigation. Process of determining the spatial location of surgical instruments and anatomic structures in real time for the purposes of guiding surgical gestures during surgery.
Navigation images. Images created by a navigation system for the purposes of navigation. Synonyms: Active display, navigation display, real-time visualization.
Navigation system. System that shows the current location of surgical instruments with respect to images of the anatomy.
and continuously updates this image as the instruments and bone structures move. It requires tracking, registration, visualization, and validation. Synonyms: Surgical navigator, guidance system.

**Tracking**

**Line of sight.** Basic requirement of optical tracking systems in which there must be no occluding objects between the position sensor and the trackers.

**Marker.** Basic element recognized by the position sensor; can be an LED or a reflective sphere. Synonyms: Infrared light-emitting diode (IRED)

**Position sensor.** System that determines the spatial location of the trackers at any moment in time. It is an optical camera for optical systems and a magnetic field generator for magnetic systems. Synonym: Localizer.

**Tracked pointer.** Pointer with a tracker used for pointing and probing during navigation. Synonym: Digitizing probe.

**Tracker.** Rigid body with markers that are recognized by the position sensor. Synonyms: Optical localizer, 3D localizer, sensor, marker carrier.

**Tracker mounting jigs.** Mechanical jigs, such as screws and clamps, used to rigidly attach trackers to surgical instrument-sand bone structures and whose purpose is to mechanically fix their positional relationship. Synonym: Attachment.

**Tracking.** Process of determining in real time the spatial location of moving objects. Synonym: Localization.

**Tracking base unit.** Unit that controls and processes the information from the position sensor and the trackers. Synonym: Tracking data acquisition unit.

**Tracking system.** System that obtains the position and orientation of trackers by measuring spatially dependent physical properties, such as optical and magnetic properties. Synonym: Localization system.

**Tracking technology.** Physical means by which the location of trackers is measured. Tracking technology is optical or magnetic. Optical tracking is active (light-emitting diodes), passive (reflective spheres), or hybrid (both active and passive), and is called semi-active. Synonym: Localization technology.

**Tracking work volume.** Volume of space covered by the position sensor in which measurements can be made. Synonym: Measurement volume.

**Accuracy**

**Accuracy.** Measure of an instrument’s capability to approach a true or absolute value. Static accuracy refers to measurements that do not change over time, while dynamic accuracy refers to time-varying measurements. Accuracy is a function of both bias and precision.

**Bias.** Measure of how closely the mean value in a series of replicate measurements approaches the true value.

**Frequency.** Number of overall measurements per second. Static accuracy refers to measurements obtained when the trackers are at rest, while dynamic accuracy refers to measurements obtained as the trackers move. Synonyms: Rate, frame rate, display rate.

**Precision.** Measure of how closely the values within a series of replicate measurements agree with each other.

**Repeatability.** Measure of resolution and stability. Resolution is the smallest discernible difference between two measurements. Stability refers to measurements made at steady state and over a sufficiently long period of time.

**Registration**

**Coordinate frame.** Fixed reference within which the spatial locations of objects can be described. Each object of interest has its own coordinate frame. Synonym: Coordinate system (COS).

**CT registration.** Process of establishing a common reference frame between the preoperative CT images and the intraoperative situation. Synonyms: Point registration, surface registration, contact registration.

**Dynamic reference frame.** Tracker attached to the bone used to track the bone motions to determine the relative location of the bone with respect to the tool. Synonyms: Reference, reference base, dynamic reference base (DRB), dynamic referencing.

**Location.** Six parameters determining the position and orientation of an object in space. Synonyms: Placement, degrees of freedom (DOF).

**Registration.** Process of establishing a common reference frame between objects and images. Synonym: Alignment.

**Registration chain.** Series of transformations that relate the locations of objects in space.

**Tool calibration.** Process of computing the transformation and the tools’ geometric features, such as its main axis and its tip position. Tool calibration verification is the process of comparing the actual and computed calibration. The tool calibration unit is the device used for calibrating tools.

**Transformation.** Mathematical description of the relationship between the locations of two objects. Transformations are static (constant) when the relative locations of the objects do not change, dynamic otherwise. There are four types of transformations: Tracking transformations, tools transformations, image transformations, and display transformations.

**Visualization**

**Silhouette.** Projection of the contours of a 3D object onto a plane.

**Viewpoint.** Location from which navigation images are created.

**Visualization.** Process of creating, manipulating, and displaying images showing the location of objects in space.

**Validation**

**Validation.** Process of verifying that the navigation images match the clinical intraoperative situation. There are three types of validation: Tool calibration validation, dynamic reference frame validation, and registration accuracy validation. Synonym: Verification.
REFERENCES


[AU6]

[AU7]

[AU8]
AU1: The term “Medtronics” has been changed as “Medtronic.” Please check.
AU2: Please clarify whether “Robodoc” shall be retained as such or should it be changed to “ROBODOC.”
AU3: Please clarify whether “Iso C-arm imaging” should be changed as “Iso-C C-arm imaging.”
AU4: The end period after the numbered list 1 to 4 under “COMPLICATIONS AND CONTROVERSIES” has been deleted to maintain consistency. Please check.
AU5: “computer-aided orthopedic surgery for skeletal trauma” has been changed as “computer-aided orthopedic surgery in skeletal trauma” to ensure consistency throughout the text. Please check.
AU6: Please check the changes made in this reference.
AU7: Please provide the names of the rest of the authors, if any, for this reference.
AU8: This reference has been deleted as its citation is missing in the text. Accordingly, the references that follow this have been renumbered. Please check.
AU9: The citations for the following four references (65, 66, 67, 68) are missing in the text. Please check.
AU10: Please clarify whether the abbreviation “IMN” shall be used in place of “intramedullary nail” at all its instances.
AU11: Please check and confirm whether the insertion made here (the subpart “G2”) is correct.