Engineering precision surgery: Design and implementation of surgical guidance technologies

Oosterom, M.N. van

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Author: Oosterom, M.N. van
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PART ONE

Engineering novel navigation modalities for fluorescence guided surgery

CHAPTER 2

SURGICAL NAVIGATION: AN OVERVIEW OF THE STATE-OF-THE-ART CLINICAL APPLICATIONS

Adapted from: Waelkens P, van Oosterom MN, van den Berg NS, Navab N, van Leeuwen FWB

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ABSTRACT

Anatomical and/or functional imaging modalities like computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound, often combined with contrast agents, and molecular imaging modalities like single-photon emission computed tomography (SPECT) and positron emission tomography (PET) have become standard tools to aid in the diagnosis, monitoring and treatment of disease or injury. Yet, translating this wealth of detailed preoperative imaging information into better surgical treatment and clinical outcome is an ongoing challenge. Patient scans usually provide a 3D map of the disease, often placed in the context of the patient's anatomy, that surgeons can use as a reference to guide them during an intervention. It would be very convenient for the surgeon to know exactly where surgical tools are on this map relative to the target location or, even better, to be provided with an optimal path from the tools towards the target.

INTRODUCTION

An analogy can be made between surgical navigation and global positioning system (GPS)-based navigation apps available on smartphones and similar devices, as illustrated in Figure 1. Smartphone navigation shows a map of our surroundings, analogous to a patient scan (Figure 1a). It shows our current location on this map (using GPS tracking), analogous to showing where surgical tools are in the image of the patient (Figure 1b). The user can mark the objective on the map, analogous to marking the location of the surgical target (e.g. tumor, lymph node; Figure 1c). Subsequently, the navigation app then suggests an optimal route between our current location and the objective, analogous to suggesting an optimal trajectory of the surgical tools to the target (Figure 1d).

Navigation is a collective term that describes any workflow where patient scans, real-time tracking, and, occasionally, computer-aided planning are combined into real-time spatial information that provides orientation (Figure 1b, c) and sometimes even guidance to reach the target location (Figure 1d) during an intervention. The main benefit of this technology is the possibility to precisely indicate where structures of interest are located relative to the surgical tools in

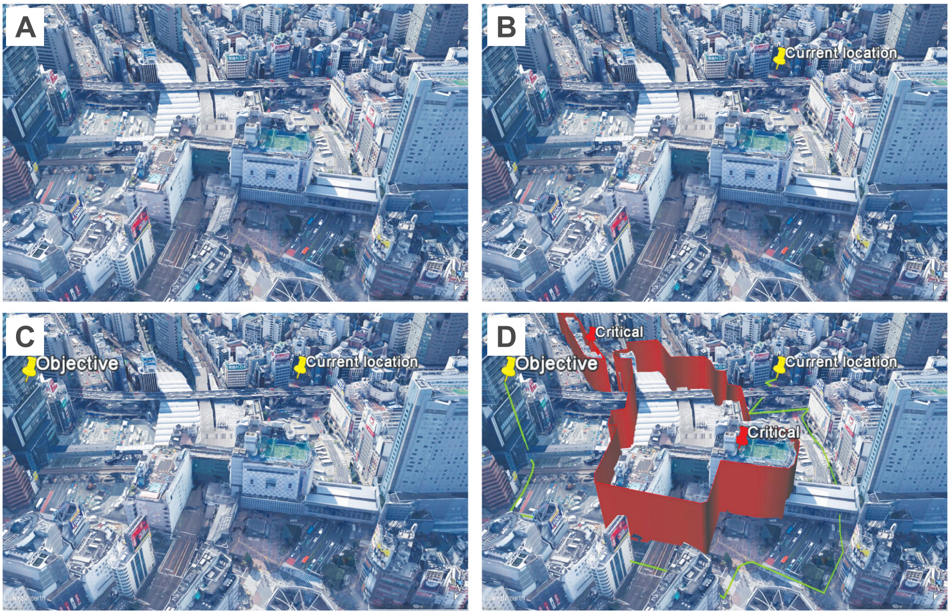


Figure 1. Analogy between surgical navigation and smartphone navigation apps. ***(a)*** *Raw 3D map of the region of interest (Depicted: Shibuya Station, Tokyo).* ***(b)*** *Current location of the surgical tools on the map, analogous to GPS localization.* ***(c)*** *The target location for navigation, i.e. the objective, can be marked on the map.* ***(d)*** *Guidance of surgical tools to the target along optimal path (in green), whilst avoiding damage to nearby critical structures. Images generated with Google Earth, satellite images provided by USGS/NASA Landsat.*

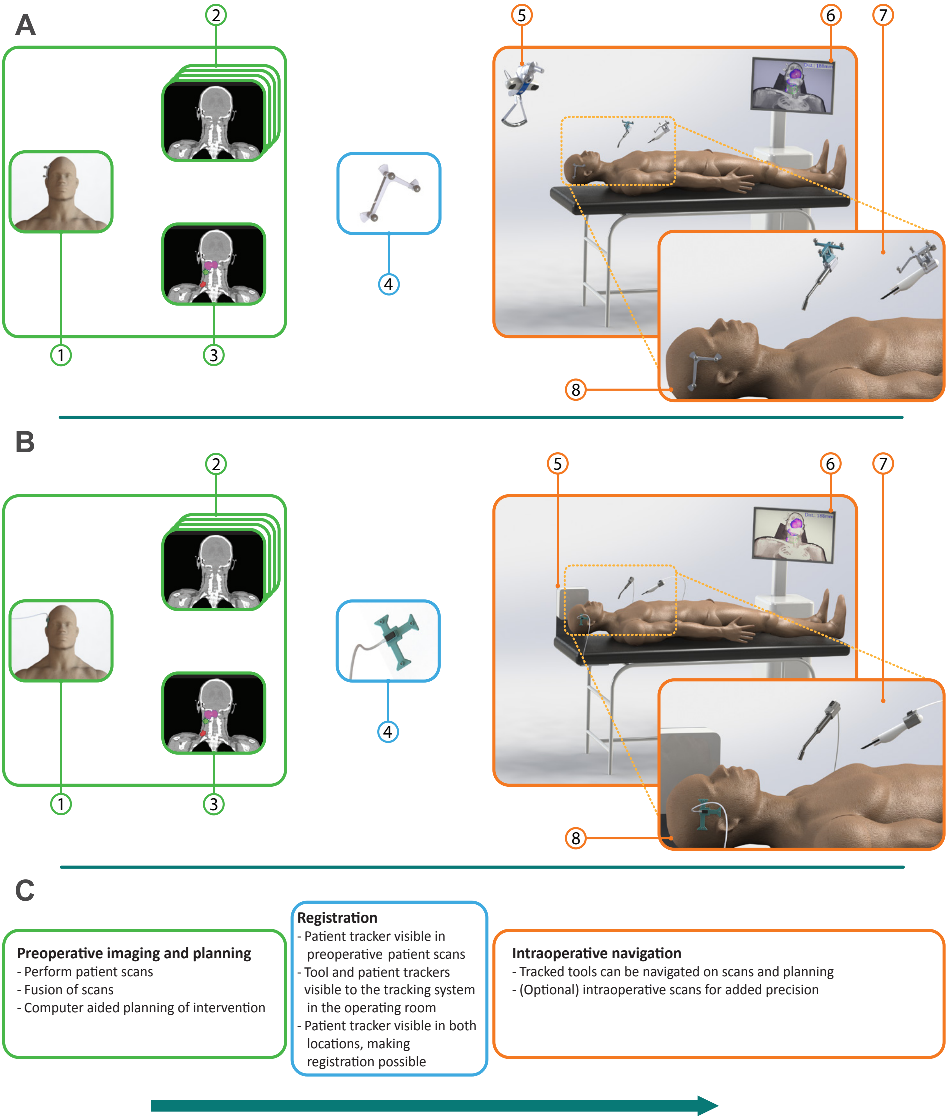
3D. This is possible even when the structures of interest are covered by tissue and cannot be seen during surgery. Although surgical navigation technologies have not yet reached full maturity, clinical evidence already suggests it is of benefit to many clinical applications. Navigation promises to bring machine precision to clinical interventions, and will likely contribute to the emergence of more precise, less invasive and, hopefully, more effective procedures.

This chapter starts with the presentation of a typical navigation workflow and the methodologies behind this approach. Subsequently a broad overview of navigation in various clinical fields, including radioguided surgery, is provided. We close the chapter with a short discussion on the presented applications and the general developments we may expect in the upcoming years.

NAVIGATION WORKFLOW

The tracking systems (Figure 2.5) are an essential component in all navigation workflows as they define the intraoperative coordinate system during an intervention. They are used to estimate the position and orientation of specially marked objects (Figure 2.7,8). These estimates, combined with registrations, enable the placement of tracked tools, patient scans and, if available, (computer-aided) planning in the same coordinate system. For object tracking, there are a number of different techniques available, e.g. near-infrared (NIR) optical tracking, electromagnetic (EM) tracking, mechanical tracking and acoustic tracking [1–4]. Of these techniques, NIR optical tracking and EM tracking are by far the most commonly used in clinical practice and will therefore be of main focus for this book chapter. With NIR optical tracking systems (Figure 2a.5), the emission and detection of NIR light is used to determine the position of trackers in space. To obtain stereo-vision, thus depth optical perception, this NIR light has to be captured by at least two cameras in a known spatial configuration. NIR optical tracking can only work when enough fiducial markers (small objects that each approximate a point and jointly representing three noncollinear points of a tracker; see next section) are in the line of sight of these NIR cameras. Marker occlusion, e.g. by surgical staff standing between the tracking system and the fiducials, is a limitation of this tracking technique and of optical tracking in general.

EM tracking systems (Figure 2b.5), on the other hand, rely on variations in the magnetic field generated by a dedicated field generator to determine the position of sensor coils present on the tracker relative to the generator. The varying magnetic field induces current and potential in the coils. Usually, multiple coils are combined into a single tracker, and the combined readings from these coils provide enough information to estimate the position and orientation of the tracker in space. Unlike NIR tracking, EM tracking systems do not require a direct line of sight to the trackers, but they have different limitations:



Preoperative imaging and planning
- Perform patient scans
- Fusion of scans
- Computer aided planning of intervention

Registration
- Patient tracker visible in preoperative patient scans
- Tool and patient trackers visible to the tracking system in the operating room
- Patient tracker visible in both locations, making registration possible

Intraoperative navigation
- Tracked tools can be navigated on scans and planning
- (Optional) intraoperative scans for added precision

Figure 2. Overview of a typical navigation workflow. (a) *Uses optical tracking and* ***(b)*** *Uses electromagnetic tracking.* ***(c)*** *Describes the sequence of steps in a typical workflow.* ***1*** *patient with tracker,* ***2*** *multiple patient scans,* ***3*** *computer-aided planning,* ***4*** *tracker visible in preoperative and intraoperative coordinate systems,* ***5*** *tracking system,* ***6*** *navigation platform,* ***7*** *tracked tools,* ***8*** *patient with tracker on OR table. CAD models of dummy human male (by LeonMaryasin) and hospital bed (by Felipe Ospina Ochoa) found in the community library of grabcad.com.*

(1) Nearby metal objects can distort the magnetic field, leading to incorrect position and orientation estimations, and (2) the working volume of current EM tracking systems is usually smaller than that of NIR optical tracking systems.

Tracking

Patient Tracking

In most navigation workflows, the purpose of tracking surgical tools is to determine their position relative to the patient's anatomy and the diseased tissue therein (as in Figure 1b) as such to better guide the surgeon during the procedure. The typical navigation workflow will make use of preoperative imaging, meaning that the preoperative imaging data set (Figure 2.1-3) has to be coupled to the interventional intraoperative coordinate system (Figure 2.5-8). The trick used to achieve this preoperative and intraoperative co-registration is to place a special tracker (Figure 2.4) at the same position on the patient during preoperative imaging and during the intervention. This tracker is, by design, both visible to the tracking system and easily segmented from the preoperative scan. Once segmented, the position of the tracker relative to the patient can be calculated, leading to a registration between the coordinates of the patient and the tracker.

To use the patient scan as a 3D map that is accurately positioned in the intraoperative coordinate system, the patient-to-tracker registration has to be coupled to the tracked position of the tracker in the intervention room. Essential requirements for precise registration are the identical placement of the tracker during preoperative imaging and during the intervention, and as little tissue deformation as possible between imaging and the intervention.

A tracker is an object that is visible to the tracking system and holds enough information for the tracking system to unambiguously establish all six degrees of freedom of the tracker in 3D space (three degrees of freedom for the position and three for the orientation). Trackers can be attached to surgical tools or to portions of the patient's anatomy, enabling their tracking (Figure 2.7,8). To accomplish tracking, the position of at least three noncollinear points must be monitored, as we illustrate in Figure 3. Most trackers are designed to be clearly visible to the tracking system and easy to segment from patient scans, as seen in Figure 2.4. Such trackers are visible both in the preoperative and in the intraoperative coordinate systems, providing the link between them and making registrations possible. The composition of a tracker is dependent on the tracking technology that will be used during the procedure. For example, NIR optical trackers (Figures 2a.4 and 3) consist of a rigid frame holding multiple (usually three noncollinear, sometimes more) fiducial markers. A fiducial marker is a small object that approximates a point. Most NIR fiducial markers are both clearly visible in preoperative scans and clearly visible to the tracking system. On the other hand, a modern EM tracker usually consists of a bundle of sensor coils inside a small case (around 0.5 cm^3) attached to a cable (wireless variants exist [5], but are uncommon) (as an example, the small black box attached to the surgical tools on Figure 2b.7 is an EM tracker). An EM tracker variant that is visible in patient scans (see Figure 2b.4) consists of a standard EM tracker attached to a frame that is large enough to be easily segmented in the patient scans.

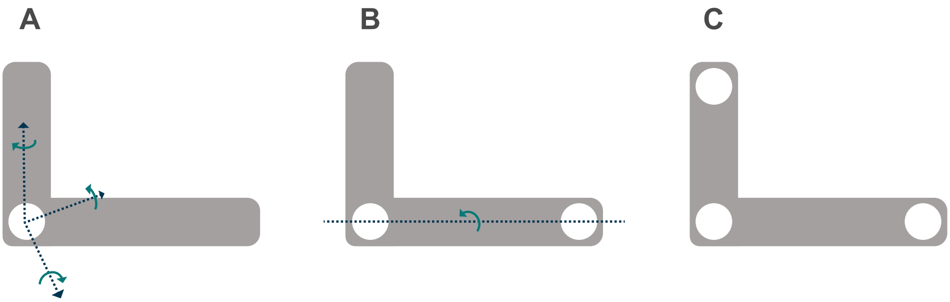


Figure 3. Fiducial markers on a rigid tracker. (a) *One fiducial, no orientation information* ***(b)*** *Two fiducials, orientation around dotted line unknown* ***(c)*** *Three noncollinear fiducials, unambiguous position and orientation*

The (EM and NIR optical) trackers described above provide a simple way to perform tracking and registration to the patient scans; of course, more complicated alternatives exist. For example, instead of a tracker, multiple loose fiducial markers can also be used to track the position and orientation of an object, provided at least three fiducials are noncollinear. This is equivalent to using a tracker, since both approaches provide enough measurements to cover the six degrees of freedom. Some authors report the use of fiducials which are visible in the patient scans, but not to the tracking system. For example, Krücker et al. [6] reported placing such fiducials on the patient's skin. During the intervention, the position of the fiducials then had to be marked by a tracked pointer, thus providing the connection between patient scans and tracking system.

Tracking of Surgical Tools

A similar, but simpler, approach is used to determine the position of the surgical tools in the intraoperative coordinate system. For this, a tracker is attached to the surgical tool that needs to be navigated. Here it is crucial that this tracker is placed at a predefined position on the surgical tool (see Figure 2.7), and that the tool is calibrated relative to the navigation platform. This calibration, in combination with the tracking information of the surgical tool tracker, allows tracking of the tip of the tool (or of any other part of the tool that is relevant during the intervention) thereby providing navigation from the perspective of the tip of the surgical tool. Tools like needles are routinely tracked using the methods described above. Some authors even report tracking tools to aid in implant placement [7–9]. Aside from surgical tools, it is also possible to track (handheld) imaging systems (e.g. ultrasound probes, gamma probes, portable gamma cameras and portable fluorescence imaging systems) as will be discussed later. A tracked scanning procedure performed with a handheld imaging system is referred to as "tracked freehand imaging".

Limitations and Implicit Assumptions of Tracking

Most navigation workflows make an implicit assumption about the body that is being tracked, namely, that it is a rigid body, i.e. that it has exactly the same shape any time during preoperative imaging and during surgery. If a body does not deform, it is sufficient to track the position and orientation of a tiny portion of it to know where the rest is. This is the justification for only placing a single tracker and/or a minimal amount of fiducial markers on a patient to track his or her position and orientation. Of course, the rigid body assumption may sometimes be unrealistic and can lead to mistakes. If the object being tracked is not a rigid body, the tracking approaches described in this text are, in general, inadequate. For example, a patient may change pose between preoperative imaging and the intervention without affecting the relative positions of the fiducial markers; in this case, the change in shape would not be detected by the tracking system. Surgeons must be aware of the implicit rigid body assumption of tracking systems and of the entailing limitations. In particular, it is always sensible to verify the precision of any registration between preoperative and intraoperative coordinates prior to and during an intervention, especially if a change in the shape of the patient is likely.

Current tracking systems work by tracking a relatively small number of points in 3D; in general, this is not sufficient to deal with arbitrary deformations. Some authors, e.g. Krücker et al. [6] for thoracic and abdominal cavity interventions and Matziolis et al. [10] for navigated total knee arthroplasty, report the use of a redundant amount of fiducials/trackers, providing more information than necessary to obtain the six degrees of freedom of a rigid body. As a consequence, more than one rigid body could be tracked in such a workflow. This can accommodate some kinds of movement, e.g. the movement of the tibia relative to the femur. Still, these multi-rigid, landmark-based, arrangements also make implicit rigidity assumptions on the patient’s shape, like the single rigid body case, and cannot accommodate arbitrary deformations particularly well. This said, redundant fiducials/trackers can be used to measure body deformation; if the spatial configuration changes during tracking, this information can be useful to correct, or at least explain, tracking errors during navigation. In addition, such findings may allow for elastic registrations which are a promising approach to handle body deformation (briefly discussed later in this chapter). Another reason for a redundant amount of fiducials, specific to optical tracking techniques, is that some fiducials may not lie in the direct line of sight of the tracking system; a large amount of fiducials reduces the chance that less than three noncollinear fiducials are visible.

On the other hand, images acquired with tracked freehand imaging are, due to tracking, automatically located in the intraoperative coordinate system; this means such images are already in the same coordinate system as the tracked surgical tools, rendering a registration between preoperative and intraoperative coordinates unnecessary. As a consequence, navigating tools in tracked

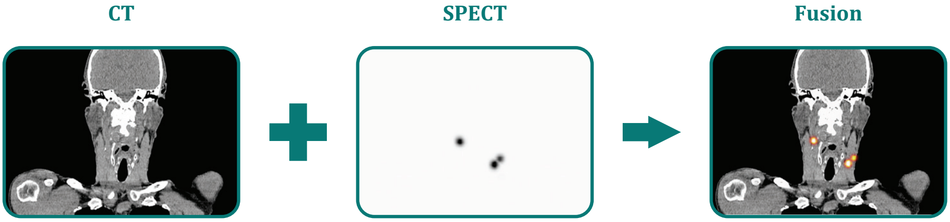


Figure 4. Image fusion. *CT and SPECT are registered, which enables a fused visualization*

freehand imaging scans is fairly straightforward. Such workflows are already reported in literature [11–13]. In the absence of specialized (and expensive) operating rooms with integrated MRI or CT scanners, tracked freehand imaging is often the only kind of 3D imaging that can be made available in the operation room. Intraoperative imaging can also be used to help verify the progress of a procedure, to cope with patient movement and sometimes even to quickly perform 3D intraoperative scans of the region of interest [11–14]. Tracked freehand ultrasound [15] is already available. An interesting novelty, especially for radioguided surgery, is tracked freehand SPECT, a SPECT generated from a tracked portable gamma camera [12, 13, 16–18].

Registration and Fusion

In the previous section, we explained how two coordinate systems (preoperative with patient scans and intraoperative with tracking information) can be connected via tracking of trackers, allowing objects from both coordinate systems to be shown in a single coordinate system. This connection between coordinate systems is called a registration. Since combining the complementary information of different patient scans allows for a more complete model of the patient, e.g. in the form of PET and MRI data, the registration concept described in the previous section should be expanded to more than two coordinate systems. This is readily possible using image registration. In fact, it is possible to register an arbitrary number of coordinate systems in a chain of registrations.

In a typical navigation workflow, all preoperative scans (Figure 2.2) are registered to each other. In at least one of these preoperative scans, the patient has to be outfitted with a tracker (Figure 2.1); this scan is then used to register the preoperative and intraoperative coordinate systems. With this registration, all other preoperative scans are also (indirectly) registered to the intraoperative coordinate system and can be navigated on. Registered patient scans are sometimes shown in composite views, where information from multiple scans is condensed into a single “fused” visualization, as illustrated in Figure 4. Note that registering multiple patient scans (i.e. performing image registrations) is often a complex and error-prone task, especially when there is deformation in the patient’s anatomy between scans. For this reason, image registrations should always be critically evaluated for errors and imprecisions prior to their use for navigation (or planning).

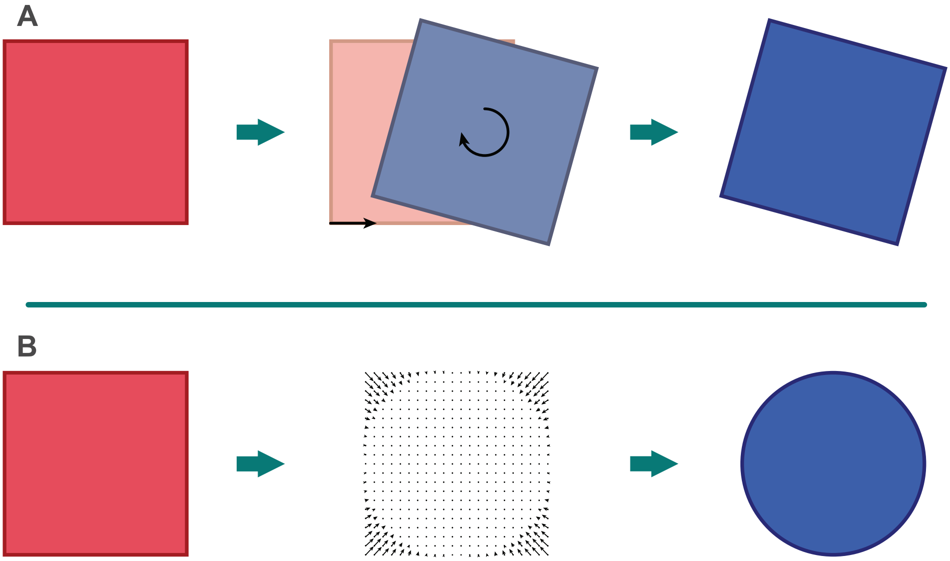


Figure 5. Types of registration. *(a) Rigid registration, a composition of rotation and translation. (b) Elastic registration, a deformation field is applied to warp the square into a circle.*

Registration methods can be separated into two types: rigid and elastic. A registration that consists exclusively of a composition of rotation and translation is called a rigid registration (see Figure 5a). Rigid registrations can always be described by a transformation matrix. The vast majority of registrations currently performed in clinical practice, including most registrations using trackers or fiducials, are rigid. Rigid registrations are relatively easy to understand, fairly simple to verify, correct, and often precise enough for the intended application. But rigid registrations are, by definition, limited in the degrees of freedom that they can accommodate.

A very common example of rigid registrations is a SPECT and CT registration (see Figure 4). Here a hybrid imaging device combines a measure of the distribution of a radiotracer (SPECT) with a scan of (CT) the patient's anatomy in a single imaging session; no significant patient movement is assumed during imaging, so the transformation matrix for this rigid registration is the identity matrix. Since many clinical applications only require a good alignment inside a small region of interest, rigid registrations will often be sufficient, even if a correct rigid alignment of the whole scans is not possible. In the cases where rigid registrations are not adequate to align scans as a result of extensive tissue movement, e.g. breast MRI scans [19] or preoperative to intraoperative brain scan alignment [20, 21], other types of registration are required.

Registrations that can handle arbitrary deformations, meaning random tissue movements, are called elastic or deformable registrations (see Figure 5b). Elastic registrations cannot be described by a transformation matrix, due to their complexity. Instead, they are described by deformation fields. Elastic registrations are the topic of image analysis papers for decades already, but their use in clinical practice has been very limited thus far. The main reason for this is that there is a trade-off between flexibility, the ability to handle arbitrary deformations, and robustness, the ability to consistently yield reasonably precise registrations. There is not one sweet spot between flexibility and robustness that works for all clinical applications, meaning an elastic registration algorithm has to be fine-tuned for each specific application. This, combined with the difficulty of finding an elastic registration method that works for the target application in the first place, greatly lowers the appeal of this technology, compared to the more generally applicable rigid registrations.

Computer-Aided Planning

Tracking and registration enable us to see the position of the tracked surgical tools overlaid on patient scans. The distance or the preferred route towards the target cannot be established with this information alone. Computer-aided planning software provides the navigation platform with the additional information needed to achieve both distance and route (Figure 1c) estimates. To enable such planning, it is necessary to segment (i.e. define the boundaries of) the target structure in the patient scans and provide this segmentation to the navigation platform. For some surgeries, damage to critical structures must be avoided at all costs; in such cases, navigation from point A to B in a straight line does not suffice (Figure 1c).

Here navigation can be further improved to navigation along a path that avoids damage to nearby critical structures, as schematically shown in Figure 1d. In order to provide such a “smart” route towards the target structure, it is also necessary to segment all critical structures that need to be avoided. To further clarify this approach, we illustrate how computer-aided planning fits into a navigation workflow by considering the resection of a kidney lesion (see Figure 6). The starting point is the patient scan shown in Figure 6a. If computer-aided planning is used, the kidney lesion and nearby critical structures are segmented (Figure 6b). This segmentation can then be used to compute an optimal trajectory to the target (Figure 6c). This plan is transferred to the navigation platform and can be used to position the surgical tools along the computed optimal path.

In computer-aided planning, manual and semi-automatic segmentations are currently the tools of choice in clinical practice. Manual segmentations, as their name implies, require manual drawings of the contours and interior of all structures that have to be segmented. The main advantage of manual segmentations is that the user has complete control over what label each voxel in the 3D preoperative scan gets. However, manual segmentations can be extremely time consuming, especially for high-resolution 3D scans. Among all segmentation methods, manual segmentations, unsurprisingly, also suffer from the highest interobserver variability. A semi-automatic segmentation is a manual segmentation with some automatic assistance. For example, a drawing tool that

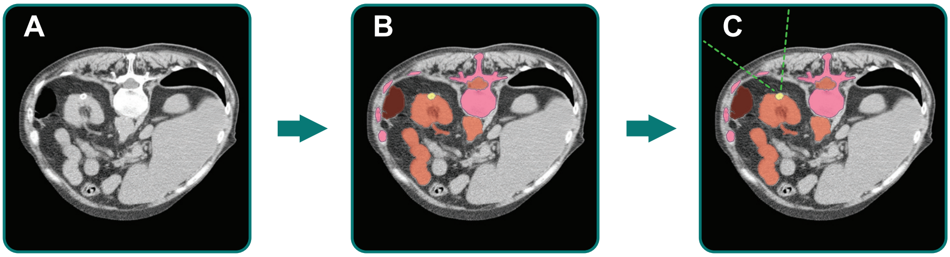


Figure 6. Computer-aided planning in the treatment of a kidney lesion. (a) *Raw patient scans* ***(b)*** *Segmentation of kidney lesion (yellow), nearby critical structures (orange) and nearby bones (pink)* ***(c)*** *Optimal paths to lesion (green dotted lines); as short as possible whilst avoiding damage to critical structures.*

automatically fills surrounding voxels of a similar color, or, for example, a tool for vessel segmentation, where only the start and endpoint of the segment have to be defined manually. Semi-automatic segmentations require far less user input and can be performed significantly faster and with higher reproducibility than manual segmentations. On the other hand, the user partially surrenders the segmentation process over to the computer, thereby reducing his or her personal touch. Automatic segmentations, and in particular atlas-based segmentations [22], have improved a lot in recent years and are slowly gaining more acceptance.

A fully automatic segmentation is a segmentation that requires no user interaction. The obvious advantage of automatic segmentations is that they neither need to be performed nor supervised by a trained medical specialist. Experienced human operators, whilst usually superior to automatic methods, are subject to time constraints and susceptible to boredom, unlike machines. These time and boredom constraints are not limiting when a single segmentation of a target structure has to be performed, but can become an issue when repetitive or more extensive segmentations are required. For example, segmenting all bones in thousands of full-body scans for an anatomy experiment would certainly yield interesting insights, but very few experts would volunteer for such a tedious task. Computers do not get bored; as a consequence, they can provide much more extensive segmentations than could reasonably be expected from a human expert. It goes without saying that automatic segmentations always have to be critically evaluated by an expert.

CLINICAL APPLICATIONS OF NAVIGATION

Attempts at surgical navigation have already been reported as early as the year 1889 [23]; these involved stereotactic frames combined with generic atlases (i.e. maps) of the anatomy, used as reference during the procedure. Due to the anatomical variation found in humans, generic atlases cannot be correct for all anatomical regions of all patients; hence, they are often not reliable for precise guidance. Patient-specific approaches to navigation, where patient scans are used instead of generic atlases, only became realistic with the development of 3D imaging technologies like CT and MRI, that became commercially available in the 1970s [24] and 1980s, respectively. We focus on patient-specific navigation approaches in this chapter and do not delve further into publications from before the time of 3D imaging.

Neurosurgery is one of the pioneering fields in surgical navigation; 3D navigation experiments are reported as early as 1986 [4]. Additional neuronavigation systems and studies are reported in the 1990s, e.g. by Germano et al. [25] and Gumprecht et al. [26], among many others. The navigation workflow described in these works corresponds to the "typical" navigation workflow seen in clinical practice today, namely, navigation of the surgical tools in preoperative patient scans. The most important limitation of this approach can be seen when the intraoperative reality significantly deviates from the anatomy depicted in the preoperative scans. In this case the estimated position of the tracked tools relative to the patient's anatomy can be off by many centimeters, negating the precision benefits navigation is supposed to bring. Outside its application in neurosurgery and in external beam radiation therapy (not discussed in this chapter; see Khan et al. [27] for a review on radiation therapy), navigation is not very widespread in clinical practice thus far, even though many other clinical applications could greatly benefit from a well-thought-out navigation workflow. Mounting evidence of navigation's benefits for particular types of treatment, ideally combined with a greater awareness of what is technically feasible, should slowly change this state of affairs. To grant the reader a short overview of how navigation can be applied in various clinical fields and what the current limitations are, the remainder of this section presents selected research on needle placement, navigated resections, and navigation in orthopedic surgeries.

Needle Placement

The objective of a needle placement procedure is to insert a needle into the patient so that the tip of the needle is as close as possible to the target location. Needles can be used to obtain biopsy samples, radio-frequency (RF) ablations, micro-wave ablations and electrode placement, among many other clinical applications. Some of these applications require a very precise needle placement, and it is expected that these will benefit most from navigation. The main challenge encountered during needle placement is that both the target location defined on imaging and, once the insertion begins, the needle tip are not visible to the physician. To compound these difficulties, the tissue (or needle) may deform during or as a result of the needle placement.

Needle navigation workflows combine patient scans with needle tracking. With tracking (and registration of the tracking system to the patient scans), the estimated (3D) position of the needle tip in the anatomy can be shown in real-time on all patient scans. In most needle navigation workflows, the target location is marked on one of the registered patient scans, as in Figure 1c; this way the navigation platform can indicate the current needle trajectory or estimate the shortest route from the needle tip to the target location. A more sophisticated workflow could also incorporate the segmentation of critical structures along the possible paths of the needle, allowing for the selection of an optimal path towards the target location whilst avoiding damage to critical structures, as shown in Figure 6c.

Stereotactic needle navigation is already used for decades to aid in the placement of electrodes for deep brain stimulation [28]. For more sophisticated navigation procedures, needles are usually tracked with the NIR optical or EM tracking systems. NIR optical tracking requires the tracker to be in direct line of sight of the cameras, meaning the tracker must be attached to a portion of the needle that is not inserted into the patient. Depending on the precision of the tracking system, and the distance from the tracker to the needle tip, aggravated by the possibility of needle bending, estimates of the needle tip position using NIR optical tracking may be somewhat imprecise. EM tracking does not possess the direct line of sight limitation, and trackers could be attached anywhere on or inside the needle. A particularly interesting recent development are miniaturized EM trackers with less than 1 mm in diameter, i.e. narrow enough to be placed inside needles. As a consequence, EM tracking can now be used to directly track the tip of a needle [29]. Additionally, multiple EM trackers can be used to monitor the bending of needles [30].

Müller et al. [31] investigated needle navigation for soft tissue biopsies, using NIR optical tracking. Navigated and conventional CT-guided liver needle biopsies were compared in five pigs, with a total of 20 tumors biopsied. The authors report that the navigated biopsies, on average, involved significantly fewer CT scans ($p = .01$) and lower dose length products ($p = .001$) compared to the conventional biopsies. Krücker et al. [6] describe the navigation of needles for biopsies and RF ablations, mostly targeted at liver and kidney lesions. Their trial involved 51 navigated needle placements in 40 procedures with a workflow consisting of segmenting the needle target location in preoperative CT scans, sometimes combined with PET scans. During the intervention, navigation of the (EM) tracked needle was combined with conventional ultrasound and 1–5 intraoperative CT scans, to make a correct placement more likely. Both during registration and needle placement, the patient needed to hold his or her breath, to minimize registration errors. The authors compared the precision of conventional image guidance with that of navigation for 19 targets (liver, kidney, neck and paracardiac mediastinum). The authors report a significantly ($p = .0006$) better precision using navigation: range [0.4–12.1 mm] with median 2.5 mm, against range [3.3–81.9 mm] with median 14.8 mm. Additionally one interventional radiologist assessed the utility of all 51 placements: 22 of the placements (43 %) would be very difficult or impossible to perform without navigation and an additional 24 placements (47 %) were facilitated by navigation. This study puts needle navigation in a very positive light, though the authors point out that the number of patients was relatively small and that a statistically meaningful comparison of outcomes with a control group was not performed.

Ungi et al. [11] propose a radiation-free, ultrasound-only workflow for navigated facet joint injections. The assumption is that this workflow yields the same clinical outcome as alternatives using fluoroscopy or CT imaging, whilst minimizing radiation exposure of the patient and surgical crew. The suggested method would work as follows: (1) a tracked freehand ultrasound scan of the spine segment to be treated is performed prior to needle insertion; (2) after imaging, the target location is segmented in the reconstructed 3D ultrasound volume; and (3) the tracked needle is then navigated to the target. Recall that both tracked tools and images acquired with tracked freehand imaging are in the intraoperative coordinate system, so, in this case, no registration step is required prior to navigation. A particular problem in conventional ultrasound-guided needle placement is that the ideal needle path is often blocked by the transducer during insertion. Hence, separating the imaging and needle insertion steps is a sensible approach. The authors performed 100 facet joint injections in cadaveric lamb models, 50 using the conventional ultrasound-guided method and 50 with the suggested (navigated) method. This increased the insertion success rate 94 % vs. 44 % and significantly shortened insertion times.

Navigated Resections

The surgical removal of all, or part, of an organ, tissue or structure is often performed to treat diseases like cancer. To avoid recurrences, it is important to remove all tumorous tissue during surgery. Ideally the tumor should not be pierced during surgery, to avoid the spillage and possible spread of tumor cells. To accomplish both a thorough tumor removal and minimize spillage, surgeons usually define a safety margin surrounding the tumor and perform the resection around this margin; all tissue inside the safety margin is removed. The resected specimen is then sent to pathology to check for positive margins, i.e. the presence of tumor cells in the edges of the excised specimen. Ideally, pathology should confirm negative specimen margins in all tumor resections. Unfortunately, this is not always the case; for example, Jacobs [32] cites reports of positive margin findings ranging from 20 % to as high as 70 % for partial mastectomies. Identification of the boundary between the diseased and healthy tissues can be addressed by the use of tracers, especially radionuclides, as described in detail in other chapters of this book. Imprecise surgical resection, can probably be improved by navigation. For example, navigation is widely used to resect brain tumors; some of the first navigation systems were designed for neurosurgery applications [2, 25, 26]. On the one hand, the brain is quite susceptible to damage, so surgical interventions should be as precise and minimally invasive as possible, yielding good disease treatment whilst minimizing the chance of permanent neurological damage. Moreover, the brain is embedded in a rigid bone case (the neurocranium), meaning it does not deform significantly between imaging and surgery. This strong need for precision combined with the favorable rigidity of the target anatomy led to the development of clinically and commercially successful neuronavigation systems (using NIR optical tracking), which make use of preoperative CT or MRI scans. Over the years, attempts to integrate many neurosurgery specific tools, like pointer tools or even entire surgical microscopes [3, 26], have been reported.

Many resections, including brain tumor resections, involve significant tissue deformation during surgery, making traditional preoperative scan-based navigation progressively more imprecise. To counter this, intraoperative CT and MRI systems have been suggested [33, 34]. Due to their relatively high price, complicated logistics, large volume, and relatively long acquisition times, it is questionable if these imaging systems will find widespread adoption in clinical settings. Tracked freehand imaging may prove to be a more viable intraoperative imaging solution. Unsgaard et al. [14] describe a modern neuronavigation workflow for brain tumor resections with preoperative MRI for initial planning and multiple intraoperative tracked ultrasound scans to monitor the progress of the resection and to cope with brain shift [20]. The system used by the authors simultaneously shows the position of the tracked instruments side-by-side on the preoperative MRI and on the latest ultrasound volume. Whenever significant tissue changes occurred, a new ultrasound scan was performed and the navigation procedure was adapted. In addition to more accurate navigation, the authors report that intraoperative ultrasound was very useful in detecting residual tumor after the planned resection was performed. In their subjective experience, in over half of the 91 procedures investigated, residual tumor was discovered in resections that were otherwise considered to be complete. The system described by the authors used NIR optical tracking.

Radioguided interventions are interventions that make use of tracers, especially radioactive tracers that allow for SPECT and PET imaging; fluorescent and hybrid fluorescent-radioactive tracers are also used for some applications [35–37]. Tracers mainly aid in the detection of target structures (like tumors or lymph nodes) and in more precise refinement of their borders. Tracers can be of use both preoperatively, enabling SPECT/CT (Figure 5) and PET/CT scans, and intraoperatively, providing real-time acoustic or visual feedback from radiation or fluorescence readings [38–41].

SPECT, and to a lesser extent PET, scans are generally used to preoperatively identify the lesions that should be taken out during surgery using specialized imaging devices, like gamma probes (1D) or gamma/fluorescence cameras (2D) [42, 43]. A logical evolution of this is to track the intraoperative devices, allowing navigation of them on the preoperative images, possibly reducing the time needed and increasing the accuracy of the intraoperative radioactive hotspot localization. Brouwer et al. [44] successfully navigated a tracked gamma probe in preoperative SPECT/CT images towards sentinel lymph nodes in ten patients with penile carcinoma. Here preoperative SPECT/CT-based navigation was combined with the intraoperative acoustic feedback produced by the tracked gamma probe. Tracked gamma probes can be used even more extensively in navigation workflows, for the generation of freehand SPECT [16] scans, that can be created during both the pre- and intraoperative process. Freehand SPECT scans have a smaller field of view and may have lower resolution than traditional SPECT scans, but they can be performed with cheaper and significantly less bulky devices. A particular advantage of freehand SPECT is that multiple scans can be performed during surgery if necessary, allowing the surgeon to double-check his or her work thereby decreasing the chance of incomplete resections. Rahbar et al. [45] performed navigated parathyroidectomy combining both preoperative SPECT/CT and freehand SPECT. Other authors report performing navigated sentinel lymph node biopsies on freehand SPECT scans in, for example, breast [12] and head and neck cancer [13, 46]. Recently, Engelen et al. [47] reported on the use of the freehand SPECT technology in combination with a mobile gamma camera. Compared to the gamma probe-based procedure, the use of a mobile camera could speed up the generation of the freehand SPECT, and the sensitivity of the camera might help improve lesion resolvability. All freehand SPECT works cited here used NIR optical tracking to track the gamma probes.

With the introduction of hybrid tracers, that contain both a radioactive and a fluorescent label (e.g. indocyanine green (ICG)-^{99m}Tc-nanocolloid [38, 39, 48]), the field of radioguided surgery further expanded. These tracers can extend navigation workflows based on SPECT/CT and freehand SPECT with intraoperative fluorescence image guidance. Brouwer et al. [49] presented a proof of concept via navigation of a tracked fluorescence laparoscope towards the hybrid tracer-containing sentinel lymph node seen on preoperative SPECT/CT. Here, as soon as the fluorescence laparoscope was near enough to the sentinel lymph node, fluorescence imaging could be performed to complement the navigation. A requirement for a successful hybrid workflow is that navigation leads the laparoscope to less than 1 cm from the target location, since fluorescence signal depth penetration is only around 1 cm in human soft tissue [50]. The benefit provided by the fluorescence imaging is that a real-time visual feedback of the tracer with respect to the local anatomy is provided. This real-time feedback can be used to better cope with potential inaccuracies in the SPECT/CT-based navigation, e.g. due to patient movement and tissue deformation.

Navigated Orthopedic Surgeries

Orthopedic surgeries are performed to treat fractures and congenital musculoskeletal malformations and to replace worn out joints with implants, among many other applications. Many orthopedic surgeries, especially procedures involving implant placement, are focused on bones, making them particularly promising candidates for navigation. Bones, unlike soft tissue, usually do not deform. This rigidity should, therefore, lead to precise registrations and, as a consequence, precise navigations. The assumption is that the machine precision provided by navigation leads to a faster and more precise implant placement. This increased implant placement accuracy may lead to a better clinical outcome, e.g. increased range of motion, better joint stability, increased implant longevity and later onset of arthritis.

Rambani et al. [51] reviewed numerous applications of navigation in orthopedic surgery, with an emphasis on navigated total knee arthroplasty (TKA) and total hip arthroplasty (THA). The authors pointed out that both for TKA and THA, correct implant alignment is essential to increase implant longevity and to achieve a good functional outcome. It was assumed that navigation may improve implant alignment compared to conventional TKA and THA. However, a recent meta-analysis involving 3423 patients (33 studies) concluded that navigated TKA brings no clear benefits in clinical outcome compared to conventional TKA, whilst at the same time, the mean duration of surgery was increased by 23 % [52]. On the other hand, a meta-analysis of three THA studies (n = 250) concluded that navigation in THA improves the precision of acetabular cup placement [53]. Taking both these studies into account, the authors conclude that the potential benefits of navigation both for TKA and THA are not yet clearly proven or disproven and suggest multicenter randomized controlled trials with long-term follow-up for these procedures.

Larson et al. [7] described the navigated placement of pedicle screws in pediatric patients with congenital spine deformity. Their workflow consisted of an initial planning of the screw placement performed on preoperative CT scans. Then, during surgery, one or more intraoperative CT scans of the spine, with an optical tracker screwed onto the patient, were used for surgical navigation (as in Figure 1b). This form of navigation allowed the authors to measure the width and depth of each screw tract, allowing screw dimensions to be custom fit to each pedicle. Results of 14 patients were presented (four cases of isolated hemivertebra and ten cases of complex spinal deformations), with a total of 142 screws placed. In this study, a 99.3 % success rate was achieved, even though the majority of screws was placed in vertebrae with congenital deformities. The authors report that comparable precision for pedicle screw placement without navigation was obtained in other studies [54], albeit for patients without congenital spine deformity.

Both Rana et al. [9] and Gander et al. [8] describe the reconstruction of unilateral orbital fractures combining the use of selective laser-melted patient-specific implants (PSIs) and navigated implant placement. Gander et al. point out that inadequate implant shape and imprecise implant placement may lead to visual disturbance and aesthetically poor results. It is assumed that PSIs have a shape that better fits to the fractured anatomy and that navigation improves the precision of the implant placement. The workflow starts with a CT scan of the patient, depicting both the fractured and the uninjured orbits, followed by a computer-aided planning step to determine the desired shape of the implant. PSIs are outfitted with ridges and landmarks, which enable navigated placement. The implants are not tracked directly; instead a tracked pointer is manually placed along the implant's ridges and landmarks during navigated insertion. Once the implant is in place, the tracked pointer can be used to verify that the implant placement is precise enough, potentially avoiding the need of additional scans to verify the implant placement after surgery. The navigation is performed on the preoperative CT scan. Both groups proceed to analyze if the proposed workflow is superior to the more traditional (manually) pre-bent titanium mesh (PBTM) implants. Based on their experiments, both groups suggest PSIs are superior to PBTM implants. Unfortunately, none of the groups directly measured the impact navigation had on the procedure or on the clinical outcome; navigation was simply used in all procedures, presumably under the assumption that this would lead to more precise (or equally precise, but faster) implant placement.

DISCUSSION

In this chapter we described surgical navigation methods and their clinical applications over a broad range of medical fields. Navigation promises to bring machine precision to the operating room. Most authors reported a positive opinion of navigation, usually backed by experimental results from (small) clinical studies. Additionally, many authors expressed the subjective opinion that navigation was beneficial or helpful for their respective application; Krücker et al. [6] go as far as stating that "procedures were facilitated that would have otherwise been difficult or impossible to perform without this technology". These results place navigation in a good light, but there are some issues that still need to be considered.

We identified three navigation workflow variants in clinical practice. The first variant is navigation on preoperative scans alone, which is usually seen in interventions with no significant tissue deformation during surgery, for example, the navigated reconstruction of unilateral orbital fractures [8, 9]. The same type of navigation can also be used to bring surgical instruments close to the target location in (laparoscopic) surgeries, as reported by Brouwer et al. [49]. Navigation on preoperative scans is the most straightforward and probably most widely used navigation variant. In some cases, however, the navigation based on preoperative scans alone can become quite imprecise, especially in the later stages of an intervention, where significant tissue deformation and patient movement may have taken place. To date tissue deformation and patient movement between imaging and surgery present significant challenges to navigation on preoperative scans. Fortunately, many creative solutions to detect and deal with deformation are already reported in literature. Krücker et al. [6], who investigated navigation in the thoracic and abdominal cavities, mentioned breath holding and respiratory gating to minimize deformations. Using a redundant amount of fiducials, non-rigid movement could be detected. A second navigation variant combines navigation on preoperative scans with intraoperative scans. In this variant, the navigation on preoperative scans only provides rough guidance, and, whenever more precision is needed, intraoperative scans are taken. Such workflows are described in [6, 7, 14]. Navigation workflows using preoperative scans alone are unsuitable for many clinical applications. With the integration of intraoperative imaging into a workflow, such navigation can, however, be applied in a much broader range of settings. The final navigation variant is navigation on intraoperative scans alone. This variant has become practical with the recent emergence of tracked freehand imaging. Recall that both tracked tools and images from tracked freehand imaging are in the same coordinate system, meaning no registration between patient scans and surgical tools is required, thus leading to a simpler navigation workflow. This navigation variant is already reported by a few groups [11–13], and we expect this list to grow significantly with the more widespread adoption of tracked freehand imaging systems.

Regarding tracking technologies, both EM and NIR optical tracking are widely used both for freehand imaging and navigation. Both technologies work well most of the time. Tracker occlusion is the main drawback of NIR optical tracking; distortion of the magnetic field due to metallic objects and small working volume are the drawbacks of EM tracking. It is not yet clear which technology will become dominant. However, with the advent of miniaturized EM trackers, that fit inside needles and can directly track the tip [29], it seems EM tracking has an advantage, at least, in needle placement interventions.

Most navigation workflows presented in this chapter compared favorably to their conventional, non-navigated alternatives. This, however, is not sufficient evidence to make blanket statements about the usefulness of navigation in general. In fact, there also is evidence suggesting that navigation provides no tangible benefits during some types of surgery; for example, Bauwens et al. [52] pointed out that navigation seems to bring no benefits to TKA surgeries. Another important issue is the amount of evidence presented to back up the claims of the benefits of a navigation workflow. Randomized controlled trials (RCT) involving large numbers of patients, the current gold standard for clinical trials, have not been performed for any of the reported methods. An open question is how much and what kind of evidence is considered sufficient to prove the benefits (or lack thereof) of a navigation workflow. It is unclear how the alleged benefits of a particular navigation workflow compared to an equivalent non-navigated alternative should be measured. Perhaps precision should be measured directly, as reported by Krücker et al. in [6], where the needle angle insertion is measured both for the navigated and non-navigated workflows; based on these measurements, estimates of the procedures' precision can be calculated and compared. Or perhaps the clinical outcome after a number of years should be evaluated instead, as in the meta- analysis of TKA and THA clinical studies reported by Rambani et al. in [51]. Alternatively, the subjective opinion of an expert [6, 14] may also provide a relevant measure. Should the experience of a surgeon also influence the measure? If so, how should one combine results from multiple surgeons with different skill sets? The lack of a consensus on how to measure the benefits of a navigation workflow surely stands in the way of large clinical trials. It is unclear when, or even if, a consensus on this measure will emerge. Even if a consensus measure emerges, one should consider if RCTs are the ideal type of trial for navigation workflows. Can clinical equipoise, i.e. the existence of a general uncertainty in the expert medical community over whether a technique is beneficial or not, be assumed for all navigation workflows? If a surgical team strongly believes a navigation workflow is superior to the alternative for a specific type of surgery, is it acceptable to perform non-navigated surgery just for the sake of a more statistically sound trial? Given all these questions, chances are RCTs will not be performed for many current and future navigation workflows. Alternative ways of gathering convincing evidence should probably be investigated. It should be pointed out that convincing evidence of the clinical benefits of a technique is a precondition for reimbursement by health insurance companies in many countries, so providing such evidence for navigated workflows is essential for them to become mainstream.

Whilst navigation is not (yet) the ultimate solution to improve surgical outcomes across the board, it does seem to be genuinely beneficial in various types of surgery. Evidence suggesting better clinical outcomes in these cases combined with ever lower barriers to its adoption leads us to believe that the use of navigation will be much more widespread in the near future, hopefully contributing to better clinical outcomes for ever more patients.

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