Navigated CT-guided interventions

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Abstract
Diagnostic and therapeutic CT-guided percutaneous interventions are clinical routine in interventional radiology. Image-guided navigation systems visualize the internal anatomy during interventions in real time not necessitating continuous image acquisition. Although multiple 3D image-guidance devices have been developed and used by several surgical disciplines in the last few years, they have not yet been fully applied by the interventional radiologist. The aim of this article is to review the currently performed methods of CT-guided percutaneous interventions and to discuss the potential benefits of newly developed 3D-navigation systems.

Key words: Navigation, frameless stereotaxy, image guidance, minimally invasive therapy, image fusion

Introduction
As percutaneous minimally invasive procedures gain increasing importance, many of these (e.g. puncture of joint effusion, infiltration of muscles, etc.) are performed without any image guidance. The needle is advanced according to standardized guidelines on the basis of anatomical landmarks which can be inspected or palpated. Imageless techniques should only be applied in anatomical regions where there is a neglectable risk of damage to vital structures and where imprecise puncture is sufficient; e.g. nerve block, where inaccurate needle placement may be compensated by increasing the dose of the applied substance.

Due to technological advancements in radiological imaging, anatomical structures that were not – or only with high risk – accessible by imageless procedures, can now be reached safely. Many different image-based percutaneous puncturing techniques have emerged in the last decades. They can be classified according to the imaging modality used: Fluoroscopy, ultrasound, CT, MRT. The choice of the optimal imaging modality is an important factor for a successful percutaneous intervention. Different modalities have their inherent advantages and disadvantages in terms of costs, availability and visibility of the target and the surrounding structures. The target and the structures at risk must be clearly visible, thus knowledge of the anatomy is the most important prerequisite for correct imaging modality selection. The application of multimodality image fusion techniques allows one to integrate information of different image datasets into the actual interventional procedure. Thus, the intervention needs not be performed with the imaging device that shows the lesion; e.g. a liver lesion which is not visible with ultrasound but with CT may still be biopsied or treated with US guidance with superimposed pre-interventional CT-MR. The aim of this article is to review the different CT guidance techniques available.

Conventional CT-guided in-plane puncturing technique
A CT scan is taken with a radioopaque grid in place. The trajectory is determined on the axial CT plane and the angle of needle entry and the depth are calculated by using electronic calipers on the CT monitor. The puncture needle is advanced manually according to the previous measurements. Due to the fact that even experienced radiologists are not able to...
estimate angles precisely according to the plan, laser guidance systems have been developed. Modern CT scanners have an integrated fluoroscopy mode, visualizing needle advancement in real-time by continuous image acquisition. At our institution the majority of CT-guided procedures including nerve root infiltrations, biopsies, sympathectomies and joint infiltrations are performed using conventional in-plane puncturing technique with laser guidance (SimpliCT, NeoRad AS, Oslo, Norway) (Figure 1).

Frameless stereotactic navigation

3D-navigation systems allow for an interactive visualization of the actual instrument position with respect to the preoperatively acquired image datasets, enabling navigation on multiplanar reconstructed image datasets in real-time. They consist of a workstation, a monitor, a three-dimensional tracking system and various pointers and instruments. Anatomic structures and instruments are assumed to be rigid bodies. At this point it is important to emphasize that current navigation systems do not compensate for elastic organ deformations (e.g. deformation of the liver and the lung during respiration, deformation of the tissue during advancement of the needle). Most currently used tracking systems are based on optic or electromagnetic principles.

Active optical tracking systems (3) consist of instruments with infrared light-emitting diodes, two or three infrared position sensor cameras and a dynamic reference frame (DRF), which has to be rigidly attached to the patient or the patient immobilization system. The DRF tracks the actual position of the patient; the camera may be moved relative to the patient without losing the spatial information.

Passive optical tracking systems improve the operator’s flexibility because they are wireless. Infrared light signals that are emitted by the charge-coupled device (CCD) cameras are reflected by passive markers and detected by the same cameras. Active and passive instruments may also be used simultaneously. As an alternative, active wireless pointers may be equipped with batteries (4). The bench accuracy of active and passive optical navigation systems is in the range of 0.1–0.4 mm (5). Navigation systems using electromagnetic sensors (6–10) do not require a “line of sight”. The tracked instruments have sensor coils at the tip. A magnetic field generator that generates multiple, electromagnetic fields is placed near the working space of the patient. The Faraday Effect induces a very small passive current in the sensor coil depending on exact distance from the field generator. The software can combine the distances from each electromagnetic field to determine location and orientation of the sensor, and therefore the instrument. Since the tip itself is tracked, flexible instruments, including endoscopes or guide wires, may be applied (11).

Important factors influencing the accuracy of frameless stereotaxy

Image acquisition

The accuracy decreases with increasing slice thickness and pixel size. The choice of the optimal values depends on the size of the target structure and the anatomical location. A slice thickness of 3 mm is sufficient for most applications. An important point is the reduction of the inaccuracy related to organ motion. Image acquisition and puncture have to be performed in the same breathing position, which may be optimized by respiratory triggering. For interventions in organs that are sensitive to respiratory motion (the liver or the base of the lung) and where a high accuracy is required, general anaesthesia may be applied in order to reposition the liver/lung. CT-acquisition, registration and puncture have to be performed in the same respiratory phase, which can be obtained by disconnection of the endotracheal tubus. Using this technique we could achieve a repositioning accuracy of 1–6 mm (mean: 1.9 mm) of the diaphragm and the related organs in 40 patients during liver punctures for radiofrequency ablation, as measured by the z-position of the top of

Figure 1. In-plane CT-guided intervention using laser guidance (SimpliCT): The laser light is kept on the hub of the needle throughout advancement.
the diaphragm in subsequent CT scans (unpublished data).

Registration

One of the key steps of navigation is the registration procedure, during which the spatial orientation of the patient is correlated with the pre-operative images of the patient. Usually this is done by attaching skin markers to the patient prior to image acquisition. A dynamic reference frame has to be mounted to the patient (or the fixation device). During the registration procedure these reference points (e.g. skin fiducials) are indicated on the real patient with the probe of the navigation system and correlated with the respective points on the image dataset. Various registration algorithms have been developed using anatomical landmarks, surfaces or artificial landmarks on the skin or on external reference frames (12–14). In the majority of cases, artificial skin markers are used. If the intervention is performed directly on the CT table, the base of reference may be taken from the CT scanner, thus allowing for automatic modality based registration (15). Alternatively, a reference frame may be imaged with the patient and automatically detected in CT images as well as with reflective markers detectable by the optical tracking system (16).

Patient immobilization

Rigid immobilization between CT acquisition and intervention is an absolute prerequisite to attain accurate results. For fixation of the head we developed the non-invasive vacuum mouthpiece based Vogele-Bale-Hohner (VBH) head holder (Medical Intelligence GesmbH, Schwabmünchen, Germany; Figure 2) (17,18), and for extracranial structures a double vacuum fixation device (BodyFix, Medical Intelligence GesmbH, Schwabmünchen, Deutschland) (19,20), respectively. A frame or a base plate enables the attachment of various instruments including the DRF and the targeting device.

Targeting device

Since the needle tip is not directly tracked by optical localization technology, an important prerequisite for a precise linear targeting is stable guidance of the instrument (brachytherapy needle, biopsy needle, radiofrequency probe, rigid endoscope, etc.) that has to be advanced into the patient’s body. Four different targeting devices for computer-assisted punctures have been developed and patented by our group in 1995 (EasyTaxis™, Philips Medical Systems, Best, Netherlands; VERTEK™, Medtronic, Louisville, USA; Atlas™, Medical Intelligence, Schwabmünchen, Germany) (21–24).

Extracranial frameless stereotactic CT-guided procedures – the Innsbruck approach

Frameless stereotactic punctures are routinely performed for the following indications:

- Biopsies, where high precision and a double angulated approach are necessary;
- Radiofrequency ablation of large tumours with multiple probes in different locations;
- Percutaneous fixation of pelvic fractures;
- Retrograde drilling of osteochondral lesions in various anatomical locations;
- Fractionated interstitial brachytherapy.

The novel technique is demonstrated in a patient in whom five retrograde drillings of an extended osteochondral lesion (3 cm in diameter) at the right femoral head were performed in one session. The patient is immobilized on the CT table with the double vacuum fixation system. Skin fiducials are attached to the patient and/or to the immobilization system (Figure 3).

A CT scan with 1 mm slice thickness of the area of interest (right hip) is obtained. The CT dataset is sent to the Treon navigation system (Medtronic...
Inc., Louisville, USA) in the CT room via intranet. Five paths are planned on 2D reformatted planes and 3D reconstructions of the patient dataset. Fat saturated 2T-weighted MR images are fused with the planning CT in order to target the subchondral edema, which is only seen in MRI (Figure 4).

In tumourous lesions pre-operative 3D positron emission tomography / single photon emission computerized tomography (PET/SPECT) data may be superimposed to the planning CT, thus the needle may be placed in the active part of the tumour according to additional biological and/or metabolic data (Figure 5). For radiofrequency ablation it is also important to plan multiple pathways in order to produce overlapping necrotic areas.

A DRF is mounted to the frame of the immobilization system and registration is performed by indicating the fiducials on the patient and selecting the corresponding markers on the 3D dataset (Figure 6).

The navigation system provides the root square mean error (RSME) which is determined by calculating the deviations of the paired-points from their true position, summing up the measurements, and then taking the square root of the sum. If the markers are optimally distributed around the volume of interest this value is a very good indicator of the overall accuracy. Usually an RSME in the range of 1 mm can be achieved. After an additional accuracy check by indicating anatomical landmarks and skin fiducials that were not used for the registration procedure, the actual navigational procedure can start. A tracked US probe may allow for superimposition of ultrasound images to the planning-CT, thus updating the image data with real-time anatomical data.

After sterile washing and draping, the targeting device is mounted to the BodyFix frame and adjusted according to the pre-operative plan.
The pin is advanced through the targeting device to the pre-planned depth (Figure 8).

A fusion of the intra-operative CT (with the needle in place) with the planning CT (with the path) is performed allowing for a precise measurement of the accuracy of the puncture (Figure 9).

The time required for set-up is about 10–15 minutes. The time from the planning CT to the placement of the needles is about 10–40 minutes, depending on the complexity of the approach and the number of pathways. Each needle/pin placement takes approximately 1–3 minutes. Using the 3D-navigation system in combination with different immobilization devices, almost every point in the whole body can be reached with high accuracy.

DISCUSSION

Conventional CT-guided interventions have gained increasing importance in interventional radiology and are currently used for various procedures such as thoracic and abdominal biopsy, thoracic and abdominal sympathicolysis, nerve root and facet joint infiltration etc. The further development and implementation of navigated CT-guided interventions is based on three principal advantages – 3D-imaging, virtual interventional planning and intraoperative 3D-guidance, which is particularly helpful when...
dealing with difficult anatomic situations, small targets or narrow surgical paths (25,26).

Conventional interventions are usually planned and performed in the axial CT-plane and positioning of the non-guided puncture needle often requires multiple control CTs, thus increasing radiation dose to the patient and procedure time. CT-fluoroscopy provides simultaneous needle manipulation and CT scanning (real-time method) or involves very short fluoroscopic CT scans, for checking only the position of the needle (quick-check method) (27,28). However, radiation exposure for the interventional team and higher exposure to the patient than with sequential CT guidance may counterbalance the advantages (29,30).

Navigated interventions provide interactive visualization of the actual position of a probe or instrument in relation to the patient in real time with free angulations in the entire 3D volume. The application of navigation systems in combination with patient fixation and targeting device allows for a precise puncture in various regions of the body at first attempt, without the need for needle position correction. Adjustable targeting devices enable rigid trajectory alignment and instrument guidance in 3D arbitrarily oriented tracks (31–33) (16,23,34,35). This can reduce needle misplacement and repeated puncture attempts and helps in achieving a predictable and reproducible result without heavy reliance on the interventionalist’s experience (36). Even tiny lesions, which cannot be reached with conventional puncture technique, can be hit. In contrast to conventional CT guided punctures, double angulated approaches are feasible with high accuracy. Especially for procedures where multiple probes must be used in order to cover the whole tumor volume adequately (brachytherapy, radiofrequency ablation, cryotherapy, etc.), 3D planning and computer assisted navigation allows for a precise 3D distribution of the needles in and around the tumor. Usually, only one planning CT and one control CT for confirmation of the correct needle position are required, which can reduce radiation dose and multiple needles (37). Many tumours are only visible after administration of contrast media and the lesion may only be seen in the contrast-enhanced planning CT and not in the control CTs. Image fusion of non-enhanced postinterventional and planning CT allows accurate evaluation of intraoperative accuracy. Integration of multimodal image fusion (CT/MRI/PET/SPECT/Ultrasound) may also improve interventional planning and execution (38).

In spite of the apparent advantages over the conventional CT-guided puncture technique, such systems are currently only rarely used by the interventional radiologist. The reasons for this are manifold and may depend on three basic requirements: Knowledge about functionality of navigation systems, familiarity and availability of such a system.

Knowledge about imaging, registration methods, different navigation systems and accuracy is essential for successful and safe application. Most navigation systems require contiguous CT-slicing without gaps or overlaps and acquisition with a tilted gantry leads to geometric distortions. CT-slices of ≤ 3 mm are recommended as there is a clear correlation of voxel size and accuracy (39–42). Registration error (43–45) is considered the most influential factor (46–48). Registration markers should be broadly distributed around the volume of interest and have to be clearly indicated on the image data and the patient, respectively (49–51). Automated registration technology – modality based navigation – can facilitate application (16,52,53). If the patient can not be immobilized he (or at least the body part of interest; e.g. a vertebra) has to be tracked via DRF to preserve registration. Immobilisation via double vacuum systems allows safe and easy patient fixation (16,54,55). Respiratory motion can make precise targeting difficult and may require reference tracking and affine transformation methods (56,57). However, when organ motion due to respiration has to be excluded, oral intubation may be required.

Optical-based systems have become standard in navigation. They offer the advantage of a high technical accuracy, convenient handling and easy sterilization. Disadvantages are the potential susceptibility to interference through light reflexes on metallic surfaces in the operating environment and the necessity of constant "line of sight" between camera-array, DRF and instruments. Possible bending of needles is not detected by the navigation system, thus only rigid instruments/needles can be tracked with high precision. This problem can be solved by using rigid targeting devices not necessitating change of the direction of the needle in the patient.

Recent electromagnetic systems have the advantages of tracking the tip of the instrument/needle by possible use of very small detector coils embedded in angiographic guide wires, endoscopes, RFA probes and biopsy needles. No visual contact between instrument and sensor system is required (58–61). Electromagnetic navigation systems may however be distorted by external magnetic fields and metal objects (62) leading to incorrect position sensing (63–65). However, magnetic referencing and tracking was found to be comparable with optical tracking both with regard to calculated and true accuracy during neurosurgery (66).
In navigated interventions, additional procedures, including system set-up, instrument calibration, registration, verification of accuracy, intraoperative application and dismantling of the navigation system may increase the operation time. Thus, familiarity with these systems is important for routine and fast use. For the application of most navigation systems, an additional person (technician) is helpful and the costs for the purchase of the guidance system (approximately 100–300,000 €) and the additional personnel costs are often prohibitive for small hospitals. Based on the advantages of navigated interventions and the large multi-purpose applicability, navigation systems may represent a valuable investment for an institution.

Conclusion

The progress in the area of image-guided and minimally invasive procedures has led to an increasing use of imaging data for planning, simulation and therapy. The spectrum of conventional CT-US-MR-guided punctures is enlarged by navigated computer-assisted puncture techniques. The 3D-guided puncture technique provides a more sophisticated planning of the percutaneous path because the puncture plane can be selected individually in 3D. Multimodal fusion imaging data for diagnostic and planning purposes and fusion of postoperative data to the initial planning data may be included. Rigid targeting devices enhance puncture accuracy and patient safety, reducing radiation dose and OR time. Since electromagnetic systems do not need visual contact between instrument and sensor system, they allow tracking of flexible instruments, compensating the possible bending of the needle. Recent automated registration (modality based navigation) will improve usability for interventional procedures. In our opinion, navigation systems will be increasingly important for the interventional radiologist. Fundamental knowledge of the basic principles, functionalities and limitations of the novel technologies is an important prerequisite for a reliable task in order to provide benefit for our patients.

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References

Potential benefits of navigation systems for CT-guidance