

Philipp Bruners  
Tobias Penzkofer  
Markus Nagel  
Robert Elfring  
Nina Gronloh  
Thomas Schmitz-Rode  
Rolf W. Günther  
Andreas H. Mahnken

## Electromagnetic tracking for CT-guided spine interventions: phantom, ex-vivo and in-vivo results

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M. Nagel  
CAS innovations AG,  
Erlangen, Germany

N. Gronloh  
Institute for Veterinary Medicine,  
University Hospital, RWTH Aachen  
University,  
Aachen, Germany

P. Bruners · T. Penzkofer · R. Elfring ·  
T. Schmitz-Rode  
Helmholtz-Institute for Biomedical  
Engineering,  
RWTH Aachen University,  
Aachen, Germany

P. Bruners (✉) · T. Penzkofer ·  
R. W. Günther · A. H. Mahnken  
Department of Diagnostic Radiology,  
University Hospital, RWTH Aachen  
University,  
Pauwelsstrasse 30,  
52074 Aachen, Germany  
e-mail: bruners@rad.rwth-aachen.de  
Tel.: +49-241-8088332  
Fax: +49-241-8082499

**Abstract** An electromagnetic-based tracking and navigation system was evaluated for interventional radiology. The electromagnetic tracking system (CAPPA IRAD EMT, CASinnovations, Erlangen, Germany) was used for real-time monitoring of punctures of the lumbar facet joints and intervertebral disks in a spine phantom, three pig cadavers and three anaesthetized pigs. Therefore, pre-interventional computed tomography (CT) datasets were transferred to the navigation system and puncture trajectories were planned. A coaxial needle was advanced along the

trajectories while the position of the needle tip was monitored in real time. After puncture tracts were marked with pieces of wire another CT examination was performed and distances between wires and anatomical targets were measured. Performing punctures of the facet joints mean needle positioning errors were  $0.4 \pm 0.8$  mm in the spine phantom,  $2.8 \pm 2.1$  mm ex vivo and  $3.0 \pm 2.0$  mm in vivo with mean length of the puncture tract of  $54.0 \pm 10.4$  mm (phantom),  $51.6 \pm 12.6$  mm (ex vivo) and  $50.9 \pm 17.6$  mm (in vivo). At first attempt, intervertebral discs were successfully punctured in 15/15 in the phantom study, in 12/15 in the ex-vivo study and 14/15 in the in-vivo study, respectively. Immobilization of the patient and optimal positioning of the field generator are essential to achieve a high accuracy of needle placement in a clinical CT setting.

**Keywords** Interventional radiology · Computed tomography · Navigation

### Introduction

Image-guided diagnostic procedures like soft tissue biopsies and therapeutic interventions like selective nerve blocks require an exact placement of usually needle-shaped devices. To ensure the required accuracy of needle placement, real-time monitoring of the device position is crucial. Therefore, for image guidance, different cross-sectional imaging techniques are used, which all have their inherent limitations. Computed tomography (CT) provides a high spatial resolution and a good bone to soft tissue

contrast but is associated with radiation exposure for the patient and interventionalist, especially if multiple control images or CT fluoroscopy for the verification of the needle position need to be performed. Different devices have been developed for the visualization of skin entry point and planned trajectory using laser light [1] but also systems which allow for needle navigation and tracking. Navigation and tracking systems visualize the actual position of the instrument used with respect to a three-dimensional (3D) image dataset, which was acquired before intervention. These navigation systems can either work with optical

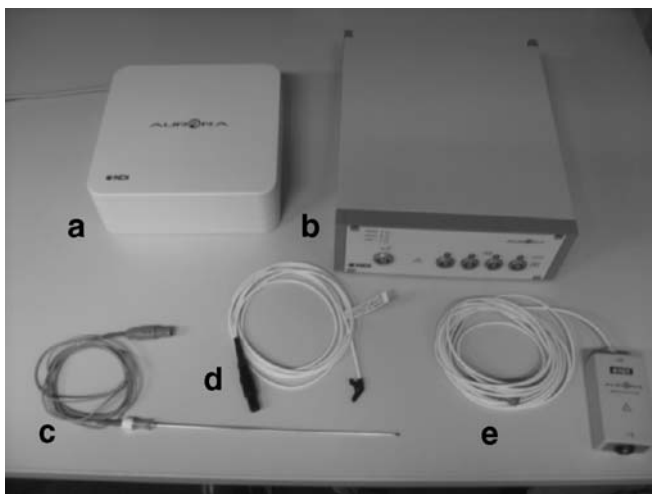
markers and cameras or based on an electromagnetic field which induces a voltage in coils being integrated into the tools used. Recently, an electromagnetic-based navigation system (CAPPA IRAD EMT, CAS innovations, Erlangen, Germany) for CT-guided interventions was introduced, for which a technical error of 0.6 mm was measured [2].

The aim of our study was evaluate the accuracy of this navigation system for CT-guided spine interventions, performing phantom, ex-vivo and in-vivo experiments.

## Materials and methods

### Electromagnetic tracking and navigation system

The navigation system mainly consists of an electromagnetic tracking system (AURORA, NDI, Waterloo, Ontario, Canada) (Fig. 1) and a commercially available PC mounted on a mobile rack with a touch screen working as the user interface. The AURORA-tracking system features a generator which produces an alternating electromagnetic field with a cubic shape and an edge length of 500 mm. The electromagnetic field induces a voltage in a coil, which is dependent on the position and orientation of the coil within the field. The induced voltage is measured by the navigation system, followed by the calculation of the position and orientation of the coil in 5 degrees of freedom (df). For the interventions performed in this study, we used a 14-G coaxial needle (200-mm length) with a small coil (diameter: 0.9 mm; length: 8 mm) integrated into the tip of the device. For image-to-patient registration a plastic panel (130 mm×60 mm×13 mm) was used, which is equipped with five radiopaque markers (4.5-mm diameter) and an additional 6-df sensor. The radiopaque markers are automatically detected in the pre-interventional CT dataset



**Fig. 1** The parts of the electromagnetic tracking system used. **a** Field generator, **b** control interface unit, **c** needle with integrated coil, **d**, 6-df sensor, **e** sensor interface unit

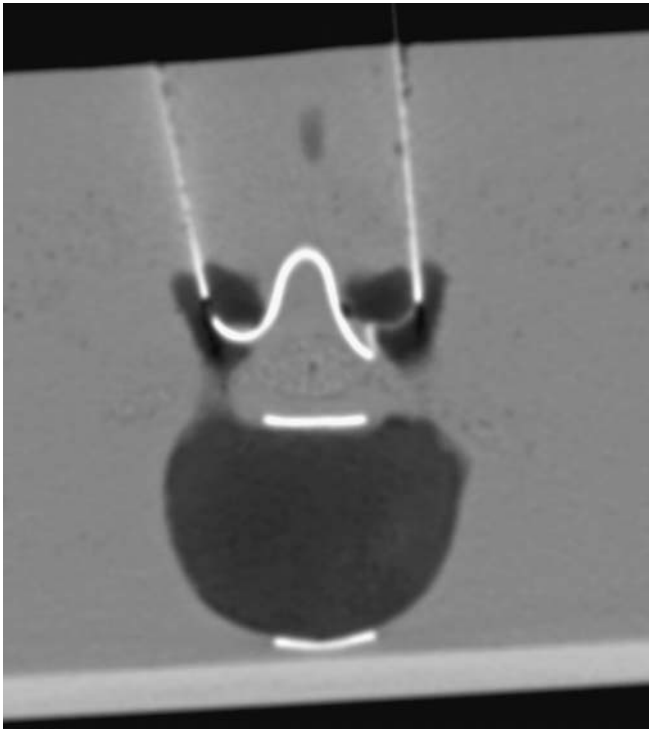
by the navigation software, whereas the tracking system detects the 6-df sensor. To allow reliable registration, the panel must be fixed in a stable position beside the immobilized patient. During intervention, the needle is visualized in the image dataset on the screen of the navigation system. The user can choose to perform the intervention in a freehand mode or use the option to plan a trajectory, which is also displayed on the screen. An additional 6-df sensor is fixed on the patient's body, usually chest or abdomen, to detect respiratory motion that is visualized as a continuous curve on the navigation monitor.

### Phantom studies

We used an anthropomorphic model of the lumbar spine that was embedded in gel wax, which simulated the surrounding soft tissue. The registration panel was fixed in a custom-made bracket beside the spine model. The phantom was placed on the CT table corresponding to a prone position for a patient. Thereafter, an unenhanced CT examination was obtained with a dual-source CT (DSCT) system (Somatom Definition, Siemens, Forchheim, Germany) applying the following CT protocol: 64×0.6 mm collimation, 120 kV, 165 mAs<sub>eff</sub>. Axial image data sets (1-mm slice thickness, 0.7-mm increment) were reconstructed and transferred to the navigation system. The generator of the electromagnetic field was mounted on a mechanical arm, which was fixed at the CT table. Afterwards, in-plane punctures of the lumbar facet joints on both sides and the intervertebral discs from lumbar vertebra 1 to the sacral bone were planned using the navigation system. Thereafter, the coaxial needle was advanced along the planned trajectory until the displayed needle tip reached the target. Then, the trochar was removed and a piece of wire was pushed through the puncture needle to mark the puncture track as previously been described [3]. After all punctures had been performed followed by the marking of the puncture tracks, another unenhanced spiral CT acquisition was obtained using the same protocol as described above. In order to analyse the distances between puncture tracks and targets, multiplanar reformations (MPR) along all puncture tracts were computed and the minimum distances between wire pieces and anatomical targets were measured. Furthermore, the length of all puncture tracks was evaluated on the basis of the reconstructed MPRs (Fig. 2).

### Ex-vivo studies

Three cadavers of domestic pigs (~50 kg) were used. Cadavers were placed and fixed on the CT table in the prone position. The registration plate was firmly attached onto the back of the cadavers using adhesive tape (Fig. 3). After that, unenhanced spiral CT was performed using the above-mentioned CT protocol and an axial image dataset was generated and



**Fig. 2** MPR based on control CT. The puncture tracts are marked with pieces of wire, indicating a successful puncture of the facet joints on both sides

transferred to the navigation system. Corresponding to the phantom studies, lumbar facet joints and lumbar intervertebral discs were punctured using the navigation system. Again, puncture tracks were marked with pieces of wire and further CT data were obtained using the CT protocol described above, followed by the measurement of the distances between wire pieces and anatomical targets.

#### In-vivo studies

Three domestic pigs (~50 kg) were included in this study after approval from the official committee on animal affairs. After pre-medication with azaperone and ketamine, all animals were intubated and mechanically ventilated with an oxygen-air mixture containing 0.8 vol.% isoflurane. Additionally, the animals received constant saline infusion in order to prevent dehydration and constant fentanyl-drip as pain-medication. Animals were placed and fixed on the CT table as described for the ex-vivo experiments. After acquisition of the unenhanced spiral CT dataset in end-expiration, reconstruction of the axial images and image transfer to the navigation system, as mentioned above, navigated in-plane punctures of the lumbar facet joints and the intervertebral discs were planned and performed. In all cases the needle was advanced during the end-expiration phase without interruption of the mechanical ventilation. Puncture tracks were

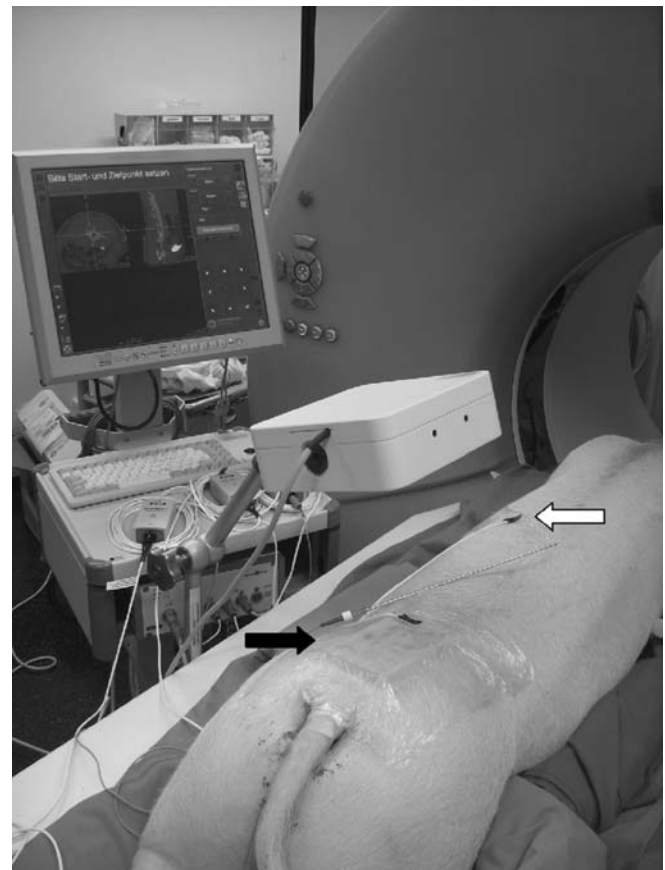
marked with pieces of wire and the distances between puncture tracks and anatomical targets were evaluated based on MPRs generated from the CT data.

#### Statistical analysis

The data were displayed as arithmetic means  $\pm$  standard deviation. After performance of an *F*-test to compare the variances, mean needle positioning errors were compared using a *t*-test for independent samples (equal variances) or a Welch-test (unequal variances). A *P* value of  $<0.05$  was considered statistically significant. Data analysis was done using Medcalc, version 9.1.0.1 (Medcalc Software, Mariakerke, Belgium).

#### Results

A total of 135 navigated punctures were performed: 30 facet joints as well as 15 intervertebral discs were



**Fig. 3** Experimental set-up for ex- and in-vivo studies. The field generator was mounted on a mechanical arm, which was fixed at the CT table. The registration plate, featuring a 6-df sensor (*black arrow*), was fixed onto the skin of the animal. An additional 6-df sensor was used for detection of respiratory motion (*white arrow*)

punctured in each experimental set-up (Tables 1, 2). The results of the *t*-tests and Welch-tests are summarized in Table 3. Compared with ex-vivo and in-vivo experiments, a significantly lower needle-positioning error was measured in the phantom study. In contrast, the mean needle positioning errors of ex- and in-vivo experiments did not show significant differences, as indicated by a *P* value >0.05. Performing the phantom study, 15 of 15 intervertebral discs were successfully punctured, whereas in the ex-vivo study the needle was correctly placed in the intervertebral disc in only 12 of 15 cases. Fourteen successful punctures of intervertebral discs were performed in the animal model.

**Discussion**

The use of navigation and tracking systems for CT-guided interventions may offer a number of advantages. A high accuracy of instrument placement avoids the damage of vulnerable structures adjacent to the target. In addition, the tracking of the instrument could reduce the need for verification scans or CT fluoroscopy resulting in less radiation exposure. For CT-guided procedures with a simple in-plane puncturing technique, such as nerve-root infiltrations, the use of optical target devices can be helpful [4]. Krombach et al. [5, 6] evaluated a laser device for CT-guided interventions and showed that the system permits accurate needle positioning. If the anatomical localization of the target resulted in an out-of-plane access route, the tilting of the CT gantry can be used to perform the intervention in-plane [7]. However, depending on the CT system used, the tilting of the gantry is usually limited to a maximum of 30° or with DSCT is not feasible at all.

Optical navigation devices are either active or passive systems. Active optical navigation systems [8] feature instruments with infrared light-emitting diodes, which are detected by two or three infrared position-sensor cameras, and a dynamic reference frame which is firmly fixed to the patient, whereas passive optical navigation devices consist of charge-coupled device cameras emitting infrared light signals [9]. The signals are reflected by passive markers attached to the instruments and received by the same cameras. One major drawback of optical tracking is the requirement of a “free line of sight” between the cameras and the optical markers. Furthermore, due to the fixation of the optical markers on the distal end of the instrument used, the position of the tip can only be calculated. Bending of the

**Table 1** Results of punctures of facet joints

Target: facet joints	Phantom (n=30)	Ex vivo (n=30)	In vivo (n=30)
Length of puncture track (mm)	54.0±10.4	51.6±12.6	50.9±17.6
Needle positioning error (mm)	0.4±0.8	2.8±2.1	3.0±2.0

**Table 2** Results of punctures of intervertebral discs

Target: intervertebral discs	Phantom (n=15)	Ex vivo (n=15)	In vivo (n=15)
Mean length of puncture track (mm)	90.7±4.8	76.0±11.7	71.4±13.8
Successful punctures/total punctures	15/15	12/15	14/15

instrument is ignored. In an experimental study comparing different optical tracking systems a tracking error of approximately 0.1 mm was shown [10]. Meier-Meitingner et al. [11] successfully used a passive optical tracking system for 14 CT-guided punctures and reported a reduction of control for CT images compared with the literature.

In general, electromagnetic tracking and navigation systems are based on the principle that a voltage is induced in coils which are placed in an electromagnetic field. The voltage depends on the localization and orientation of the coil within the field. Different systems working with this principle have been developed. Holzkecht et al. [12] used an electromagnetic navigation system for 50 CT-guided interventions and reported deviation between planned and documented needle tip position of 2.2±2.1 mm. Similar to optical navigation systems, the tracking sensor was fixed at the outer part of the needle, resulting in a lack of correction needle bending. Wallace et al. [13] successfully used the same navigation device for 20 out-of-plane CT-guided biopsies in different organs without any procedure-related complication. Another approach to use electromagnetic tracking and navigation is to integrate small coils into the tip of the used tools. Wood et al. [14] showed the feasibility to use pre-interventional magnetic resonance (MR), CT and positron emission tomography (PET) datasets for electromagnetic tracking and navigation of catheters, guidewires and needles in phantom and animal experiments using a custom developed software tool. For liver biopsies requiring an oblique access path, Banovac and co-workers showed a favourable radiation dose and procedure duration using electromagnetic tracking compared with conventional biopsies using CT fluoroscopy [15]. Both biopsy techniques revealed an equivalent accuracy in a single animal. In contrast to the presented study, a 20-G stylet containing an electromagnetic sensor was additionally inserted into the right liver lobe to detect respiratory motion. Levy et al. [16] reported the successful creation of an

**Table 3** Comparison of mean needle positioning errors

Comparison of mean needle positioning errors	<i>t</i> -test	Welch-test
Phantom – ex vivo	–	<i>P</i> <0.0001
Phantom – in vivo	–	<i>P</i> <0.0001
Ex vivo – in vivo	<i>P</i> =0.7	–

intrahepatic portosystemic shunt in an animal model also using internal fiducials placed percutaneously into the liver. In a recently published clinical trial, the spatial accuracy of an electromagnetic tracking system in combination with custom software was evaluated for CT- and ultrasonography (US)-guided biopsies and thermal ablations, resulting in a basic tracking error of 6.4–3.7 mm [17].

In our study, the lowest positioning error of the needle was achieved in phantom studies, which is explained by the immobility and rigidity of the phantom. Furthermore, the firmly attached registration plate allowed for a reliable registration due to the fixed spatial relation between the target and registration plate. In contrast, when performing the punctures in the ex-vivo model the registration plate was fixed on the skin of the cadaver proximally above the spine (Fig. 3). Despite the fixation of the cadavers on the CT table, there might have been movement between the skin with the attached registration plate and the spine below, affecting the registration and resulting in less accurate placement of the needle. No significant difference was found comparing the needle positioning errors in ex-vivo and in-vivo experiments, although the mechanical ventilation was not interrupted during the punctures in the animal study. This finding may be due to the fact that the needle was only advanced during the end-expiratory phase, which was visualized by the navigation system. In addition, we assume that there was only little influence of respiratory motion on the spatial relationship between the spine and registration plate which could have led to larger needle positioning error.

The slightly better results regarding punctures of the intervertebral discs found in the in-vivo study compared with the ex-vivo experiments may be explained by our learning curve, because all ex-vivo experiments were performed prior to the in-vivo study. Although the experimental set-up was not substantially changed, for example, the placement of field generator or the fixation of the animal on the CT table and attachment of the registration plate might have been optimized during the study. Although we did not systematically analyse the influence of these factors, we observed that immobilization of the subject as well as fixation of the registration plate played an important role for the successful performance of the navigated intervention. In addition, the position of the anatomical target in relation to the CT table may have influenced the needle-positioning error due to metal parts integrated in the CT table disturbing the homogeneity of the electromagnetic field.

In conclusion, the presented study shows promising results for the use of electromagnetic tracking and navigation in spine interventions, although only punctures of the lumbar spine were performed. Further clinical studies are needed to determine the benefit of the system used in clinical routine, especially with regard to saving of radiation dose and time-effectiveness in comparison with the conventional procedure.

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