# A Buyer's Guide to Electromagnetic Tracking Systems for Clinical Applications

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## ABSTRACT

When choosing an Electromagnetic Tracking System (EMTS) for image-guided procedures, it is desirable for the system to be usable for different procedures and environments. Several factors influence this choice. To date, the only factors that have been studied extensively, are the accuracy and the susceptibility of electromagnetic tracking systems to distortions caused by ferromagnetic materials. In this paper we provide a holistic overview of the factors that should be taken into account when choosing an EMTS. These factors include: the system's refresh rate, the number of sensors that need to be tracked, the size of the navigated region, system interaction with the environment, can the sensors be embedded into the tools and provide the desired transformation data, and tracking accuracy and robustness. We evaluate the Aurora EMTS (Northern Digital Inc., Waterloo, Ontario, Canada) and the 3D Guidance EMTS with the flat-panel and the short-range field generators (Ascension Technology Corp., Burlington, Vermont, USA) in three clinical environments. We show that these systems are applicable to specific procedures or in specific environments, but that, no single system is currently optimal for all environments and procedures we evaluated.

**Keywords:** image-guided therapy, electromagnetic tracking, accuracy analysis, usability study

## 1. INTRODUCTION

To date Electromagnetic Tracking Systems (EMTS) evaluation has only focused on system accuracy and stability in the clinical environment.[1–3] In this paper we identify a comprehensive set of factors that influence the applicability of an EMTS in the clinical environment. We then evaluate two commercially available systems based on these factors as they pertain to several medical procedures.

We have previously developed image-guidance systems based on electromagnetic tracking for a variety of procedures. These include Radio Frequency Ablation (RFA) of liver tumors,[4] creation of a Transjugular Intrahepatic Portosystemic Shunt (TIPS),[5] carotid stent deployment,[6] vertebroplasty,[7] needle biopsies of liver lesions,[8] and transbronchial biopsies.[9]

These procedures are performed in three different environments: an interventional radiology suite, a CT suite, and a pulmonology suite (Figure 1). Our primary environment is the interventional radiology suite. It houses a floor mounted C-arm based cone-beam CT system, the Siemens Axiom Artis dFA, which provides both volumetric images and projection images. The first four procedures, RFA, TIPS, carotid stent deployment, and vertebroplasty, are performed in this room. They utilize tracked needles, catheters, and vertebroplasty trochars. The liver lesion biopsies are performed in the CT suite, and utilize needles. This suite houses a Siemens Somatom Volume Zoom CT machine that provides volumetric data and also real time single slice imaging, CT-fluoroscopy. Finally, the transbronchial biopsies are performed in the pulmonology suite, using biopsy forceps inserted through the flexible bronchoscope's working channel. The bronchoscope we use in this suite is the Pentax EB-1530T2. Figure 2 shows the various tools used in these procedures.

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Medical Imaging 2008: Visualization, Image-guided Procedures, and Modeling, edited by Michael I. Miga, Kevin Robert Cleary, Proc. of SPIE Vol. 6918, 69182B, (2008)
1605-7422/08/$18 · doi: 10.1117/12.770509

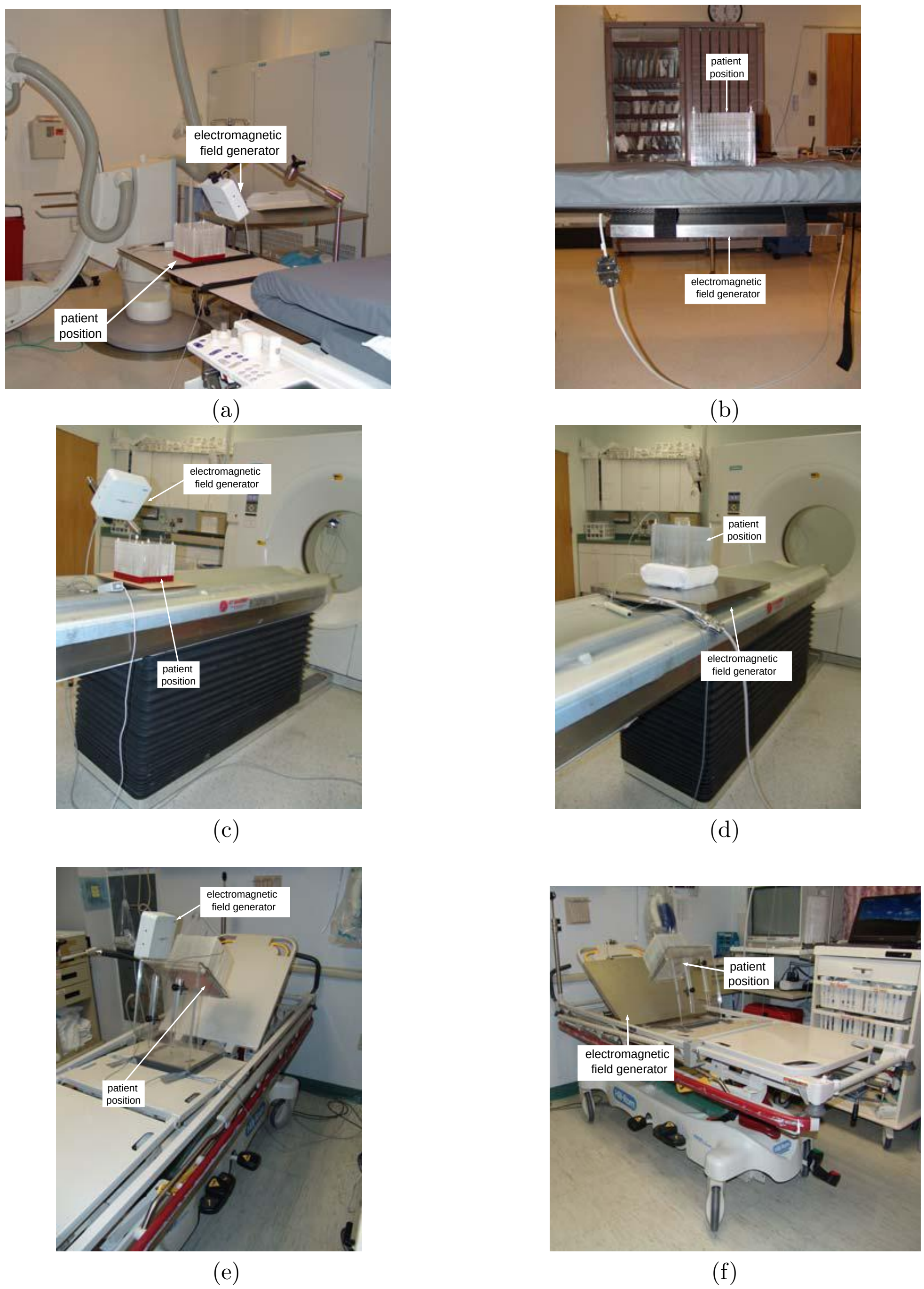



**Figure 1.** Setup of electromagnetic tracking systems in the interventional environments in which we assess their usability (a,b) interventional radiology suite, (c,d) CT suite, and (e,f) pulmonology suite. Left column shows the setup with the Aurora system. 3D Guidance short-range field generator setup is similar. Right column shows the setup with the 3D Guidance flat-panel field generator.

**Figure 2.** Tools used in the clinical procedures we study. From left to right, needle, catheter, vertebroplasty trochar, biopsy forceps.

Ideally, we would like to have a single EMTS that is applicable across procedures and environments. Based on the set of procedures enumerated above we define the following requirements from this ideal EMTS:

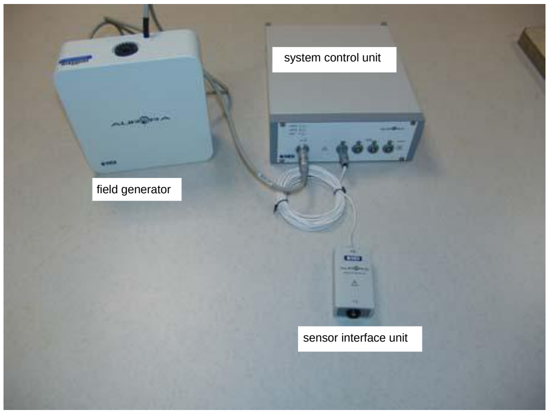
1. Speed: refresh rate of 100Hz with a latency of less than 1ms, regardless of the number of deployed sensors.
2. Concurrency: tracks up to 30 sensors concurrently (note that a flexible tool may contain multiple sensors).
3. Working volume: has an effective work volume of $5^3 m$ (room sized).
4. Obtrusiveness: sensors are wireless and can function for several hours, all hardware components can be positioned so that they do not restrict the physical access to the patient, and the system does not have any effect on other devices used during the procedure.
5. Completeness: sensors are small enough to embed in any tool and provide all six degrees of freedom (6DOF sensors).
6. Accuracy: resolution less than $1mm$ and $0.1^o$.
7. Robustness: not affected by the environment (light, sound, ferromagnetic materials, etc.).

Having established the requirements from the ideal EMTS we are now ready to evaluate existing EMTS, based on the way they address these requirements.

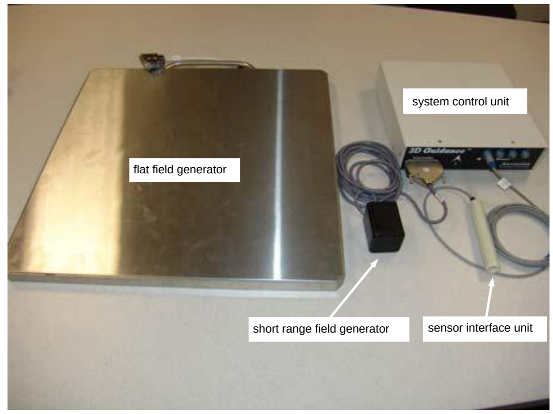
As far as we are aware, there are only three vendors for stand-alone EMTS, Northern Digital Inc. (Waterloo, Ontario, Canada),[10] Ascension Technology Corp. (Milton, Vermont, USA),[11] and Polhemus (Burlington, Vermont, USA).[12] In this study we evaluated the Aurora (Northern Digital Inc.), and 3D Guidance (Ascension Technology Corp.) systems. We did not evaluate any of the tracking systems from Polhemus, as the sensor size used by these systems is on the scale of several centimeters which precludes embedding them in any of the medical devices which we need to track.

## 2. MATERIALS AND METHODS

In this work we assess the Aurora and 3D Guidance EMTS. Both EMTS consist of three basic components, the field generator, a system control unit that interfaces with a PC, and tracked sensor coils and their respective interface to the system control unit. Note that the 3D Guidance system is evaluated in two configurations, using the flat-panel and the short-range field generators. Figure 3 shows the system components for both EMTS as used in this study.




(a)




(b)

**Figure 3.** Electromagnetic tracking systems and their components, as used in this study, (a) Aurora and (b) 3D Guidance.

From our prior experience with assessing the accuracy of electromagnetic tracking systems[3] we have observed variable performance. We thus believe that, while electromagnetic tracking is a viable option for tracking in the clinical environment its applicability should be evaluated per environment, and even more specifically on a per procedure basis.

We thus evaluate each requirement with respect to the specific environments or procedures where relevant.

## 2.1. Speed

The maximal refresh rate for the Aurora system according to manufacturer specifications is 40Hz. We empirically evaluated this by acquiring time stamped measurements using a single five degree of freedom (5DOF) sensor. Data was acquired with a program developed in house using the system's API. The refresh rate we obtained was 39.86Hz which concurs with the manufacturer's specifications. When an additional 5DOF sensor was attached the refresh rate dropped to 20-25Hz. Attaching additional sensors after this initial decrease in refresh rate did not have any effect. For our purposes this refresh rate is just sufficient as our display is updated at 25-30Hz. System latency was not assessed quantitatively. We have qualitatively observed that it was not an issue in any of our image-guidance applications.

The maximal refresh rate for the 3D Guidance system according to manufacturer specifications is 160Hz with the flat-panel field generator and 375Hz with the short-range field generator. Interestingly, the factory default refresh rate, set for optimal accuracy, for the flat-panel field generator is about 40Hz and for the short-range field generator about 68Hz. We empirically evaluated the refresh rates both for the flat-panel and short-range field generators by acquiring time stamped measurements using six degree of freedom (6DOF) sensors. Data was acquired using a custom program from Ascension. The refresh rate we obtained for the flat-panel field generator was approximately 160Hz irrespective of the number of tracked sensors. The configuration with the short-range field generator was also unaffected by the number of tracked sensors, with an acquisition rate of 190Hz.

## 2.2. Concurrency

The Aurora system supports tracking of up to eight 5DOF sensors or four 6DOF sensors. The 3D guidance system supports tracking of up to 12 5DOF sensors and eight 6DOF sensors. For all of our applications we have found these numbers to be sufficient, as less than eight tracked tools are used at the same time.

## 2.3. Working volume

The Aurora system provides a working volume of $500 \times 500 \times 500$mm. The 3D guidance system's working volume is dependent upon the electromagnetic field generator. With the flat-panel field generator the working volume is similar to the Aurora work volume. With the short-range field generator the work volume is

$1000 \times 1000 \times 1000$mm but manufacturer specifications state that optimal accuracy is limited to a sub-volume of approximately $200 \times 200 \times 200$mm.

The work volume provided by the 3D Guidance short-range field generator will require special consideration when positioning it relative to the patient. For all of our procedures, except for carotid stent deployment a work volume of $500 \times 500 \times 500$mm is sufficient. For carotid stent deployment the initial part of the navigation, starting at the femoral artery, was performed using the current clinical approach, and once the tracked volume was reached the physician was able to use our navigation system.

## 2.4. Obtrusiveness

As this requirement consists of several sub-categories it can be partially assessed independently from the procedure and environment. Both the Aurora and 3D Guidance systems are wired. That is, the tracked tools are connected via wires to the control unit. While this does not preclude any of the procedures we are investigating it does make them more cumbersome. More importantly, these additional wires require caution on the part of the medical staff when moving around the patient. If the procedure also involves moving imaging apparatus such as the rotating C-arm in the case of cone-beam CT, one must exercise caution in placing the wires as they are not an obstacle during navigation but they may be in the path of the rotating arm.

**Interventional radiology suite**

In all procedures performed in the interventional radiology suite the Aurora EMTS is placed such that the systems field generator is mounted on a passive mechanical arm positioned approximately $150mm$ from the patient (Figure 1(a)). This restricts physical access from certain directions but has not been a limiting factor in any of the procedures. The 3D Guidance system with the short-range field generator is positioned similarly. It is slightly less intrusive than the Aurora system due to the smaller form factor of the field generator. The 3D Guidance system with the flat-panel field generator does not change the physical access to the patient from current clinical practice, as the field generator is placed underneath the patient (Figure 1(b)).

In the RFA, TIPS and stent deployment procedures preoperative CT data is used for navigation and C-arm fluoroscopy is potentially used for intraoperative imaging, validating the information presented by the navigation system. The Aurora's field generator precludes imaging from certain C-arm poses. This is not a limiting factor as long as imaging and tracking are not required simultaneously, as the field generator can be easily moved out of the way. For the vertebroplasty procedure preoperative cone-beam CT data acquired with the C-arm is used for navigation. This requires additional care in positioning the field generator so that it is not in the path of the rotating C-arm. Again, this was found to be a minor inconvenience.

The 3D Guidance system with the short-range field generator is similar to the Aurora system. When configured with the flat-panel field generator we have found that because the field generator cannot be easily moved in and out of tracking position image quality is degraded. This was assessed by imaging an interventional 3D Abdominal Phantom (CIRS, Norfolk VA, USA). This phantom is composed of materials that mimic the X-ray attenuation of human tissue. We acquired both 2D projection images and a C-arm cone-beam CT reconstruction, with and without the flat-panel field generator in place. Detailed results are given in section 3.

**CT suite**

In the needle biopsy procedures performed in the CT suite the Aurora EMTS is placed such that the system's field generator is mounted on a passive mechanical arm positioned approximately $150mm$ from the patient (Figure 1(c)). This restricts physical access to one side of the patient but has not been a limiting factor in this procedure as the mechanical arm and field generator are on the opposite side of the CT bed from the physician. As was the case in the interventional radiology suite, the 3D Guidance system with the short-range field generator is similar to the Aurora system. When using the flat-panel configuration, the field generator is placed underneath the patient (Figure 1(d)). This requires that the standard mattress be replaced with one which will support the patient. This is due to the shape of the patient couch, which is curved with the flat-panel field generator raising the patient above the bed. This will also cause problems with obese patients, as the effective bore size is reduced.

In the needle biopsy procedures there are two modes of imaging, acquisition of a preoperative CT scan and intraoperative CT fluoroscopy, real time single slice imaging. The Aurora and 3D Guidance with short-range field generator are not in the field of view when imaging and thus do not effect image quality. When using the

3D Guidance system with the flat-panel field generator the images always included the field generator as it is placed underneath the patient. We performed the same imaging experiment as in the interventional radiology suite, showing that the image quality was degraded by the field generator's presence. Detailed results are given in section 3.

**Pulmonology suite**
In the transbronchial biopsy procedure the patient is lying on a strecher at a $45^o$ upright angle, with the mechanical arm holding the Aurora field generator attached to the stretcher's rail (Figure 1(e)). This restricts physical access to one side of the patient. This is not a limiting factor as the physician stands on the opposite side of the stretcher facing the bronchoscopy monitor. Again, the 3D Guidance system with the short-range field generator was similar to the Aurora system, and the flat-panel field generator is unobtrusive as it is placed under the patient's back (Figure 1(f)).

None of the systems caused any noticeable distortions of the video imaging.

### 2.5. Completeness

Both the Aurora and 3D Guidance system support 5DOF and 6DOF sensors. For the Aurora system the smallest 5(6)DOF sensors have a diameter of $0.55(1.8)mm$. For the 3D Guidance system the smallest 5(6)DOF sensors have a diameter of $0.3(1.3)mm$.

**Interventional radiology suite**
The tools that require tracking in our procedures are 18 gauge (diameter of $1.02mm$) needles for RFA, and TIPS, 22 gauge (diameter of $0.6mm$) needles for vertebroplasty, a catheter with a diameter of $2.3mm$ for stent deployment, and a vertebroplasty trochar with a diameter of $4.2mm$. All of these tools are similar in that they are used in a way that allows us to model them as cylinders. That is, the rotation around the tool axis is unimportant. This is why 5DOF sensors are sufficient for all of these procedures.

**CT suite**
The tools required for the biopsy procedures performed in the CT suite are 18 gauge needles as used in the procedures performed in the interventional radiology suite.

**Pulmonology suite**
The tool that we need to track for the transbronchial biopsy is a forcep that must fit through the bronchoscope's working channel. In our case the working channel has a diameter of $2mm$, and the forceps have a sheath diameter of $1.8mm$. For this procedure we cannot use the same cylindrical model as done for other procedures. Navigation is performed using a preoperative CT in which a virtual camera is positioned in the same pose as the bronchscope's camera which is tracked relative to the forceps. The tracked forceps are thus required to provide all six degrees of freedom. As the unknown rotation around the sensor axis is similar to an unknown camera rotation around the view direction. While the 6DOF sensors are close to the sheath diameter it has been shown that it is possible to use a 5DOF sensor to perform the tracking in combination with video-to-CT registration to compensate for the unknown rotation.[13]

### 2.6. Accuracy

The accuracy of each system was evaluated using the protocol described in.[3] A plexiglass phantom is used to acquire data measurements at 225 locations. At each location, 100 measurements are acquired and their average is used as the point's coordinates. We also record the distance of each of these 100 samples from the EMTS origin and the range of the distance variability, reflecting the system's stability. We then register the acquired point set to the phantom's coordinate system using paired-point rigid registration and compute the distance between the known point location and the reported point location after it is transformed. For the distance variability data we report on the maximal variability range:

$$\max[\max\{d_i\}_j - \min\{d_i\}_j], \quad i = 1 \dots 100, \quad j = 1 \dots 225$$

where $d_i$ is the distance from the EMTS origin to the $i$'th point. For the registered point set data we provide the following descriptive statistics: RMS error, mean error, standard deviation, error range, maximal error and 95 percentile. This experiment was performed in each of the environments described in this paper. Detailed results are described in section 3.

## 2.7. Robustness

**Interventional radiology suite**

In the interventional radiology suite the device that is potentially most disruptive to electromagnetic tracking is the C-arm. To evaluate its effect on the stability of the tracking we performed the following experiment. We first placed two tracked sensors at an unknown fixed distance from each other. We then acquired data with the C-arm in its home position away from the patient and tracking systems. The C-arm was then moved into imaging position, and an image and tracking data were simultaneously acquired. Finally, we acquired tracking data during a cone-beam CT scan. For each of these data acquisitions we computed the distance between the two sensors based on their respective transformations. Detailed results are given in section 3.

**CT suite**

In the CT suite both the patient couch and CT gantry are potentially disruptive to electromagnetic tracking. Both these components are active while a CT scan is acquired. When CT fluoroscopy is used only the gantry rotates and the couch remains stationary. To evaluate the effect of these elements on the stability of the tracking we performed the following experiment. We first placed two tracked sensors at an unknown fixed distance from each other.We then acquired data at the spatial location where we expect to perform tracking, away from the gantry. This was followed by tracking data acquisition during CT fluoroscopy imaging, and finally tracking data acquisition while a CT scan was performed. For each of the data acquisitions we computed the distance between the two sensors based on their respective transformations. Detailed results are given in section 3.

**Pulmonology suite**

In the pulmonology suite the potentially problematic equipment is the patient's stretcher itself. In our institute the procedure is performed with the patient lying on the stretcher at an angle of $45^o$. Unlike the interventional radiology and CT suites where the patient couches are fixed, the stretcher model varies, as the procedure is performed on whichever stretcher the patient is being transported with. This may result in performance variability based on the stretcher type. In our case we tested with a single stretcher type, the Hill-Rom (Batesville, Indiana, USA) P8000 transport stretcher, and thus cannot provide comprehensive conclusions.

# 3. EXPERIMENTAL RESULTS

We now describe our experimental results with regard to the effect the EMTS have on imaging, and our accuracy and robustness evaluations of these systems.

## 3.1. Effect on imaging

To assess the effect of the electromagnetic tracking systems on imaging we acquired images while tracking. In the interventional radiology suite we acquired cone-beam CT and projection images, in the CT suite we acquired a CT scan and CT-fluoroscopy, and in the pulmonology suite we acquired video images.

In all suites the Aurora and 3D Guidance with short-range field generator had no noticeable effect on image quality, as they were easily moved away from the imaged region. The 3D Guidance with flat-panel field generator did result in a noticeable degradation in image quality when acquiring cone-beam CT data, projection X-ray images, CT-fluoroscopy and standard CT data. The main cause for the loss in image quality is the presence of the field generator in the imaged region. As these images are used in subjective interpretation of the anatomical structures, we cannot determine if the lower image quality precludes the use of the flat-panel field generator. This is left up to the physician's discretion. Figure 4 summarizes these experiments.

## 3.2. Accuracy

The accuracy of each of the tracking systems was evaluated as described above. The interventional radiology suite was found to be the optimal environment for tracking. This is the only environment that can be controlled so that the distortion of the EMTS magnetic field is minimal. The C-arm, which is a potential cause for distortion can be placed in its home position far from the patient. In addition, the region of the patient table over which the EMTS work volume is positioned is suspended in mid-air. Table 1 summarizes the accuracy evaluation in the interventional radiology suite. The 3D Guidance with short-range field generator was the most accurate in this environment, with the Aurora and 3D Guidance with flat-panel field generator having comparable accuracy.

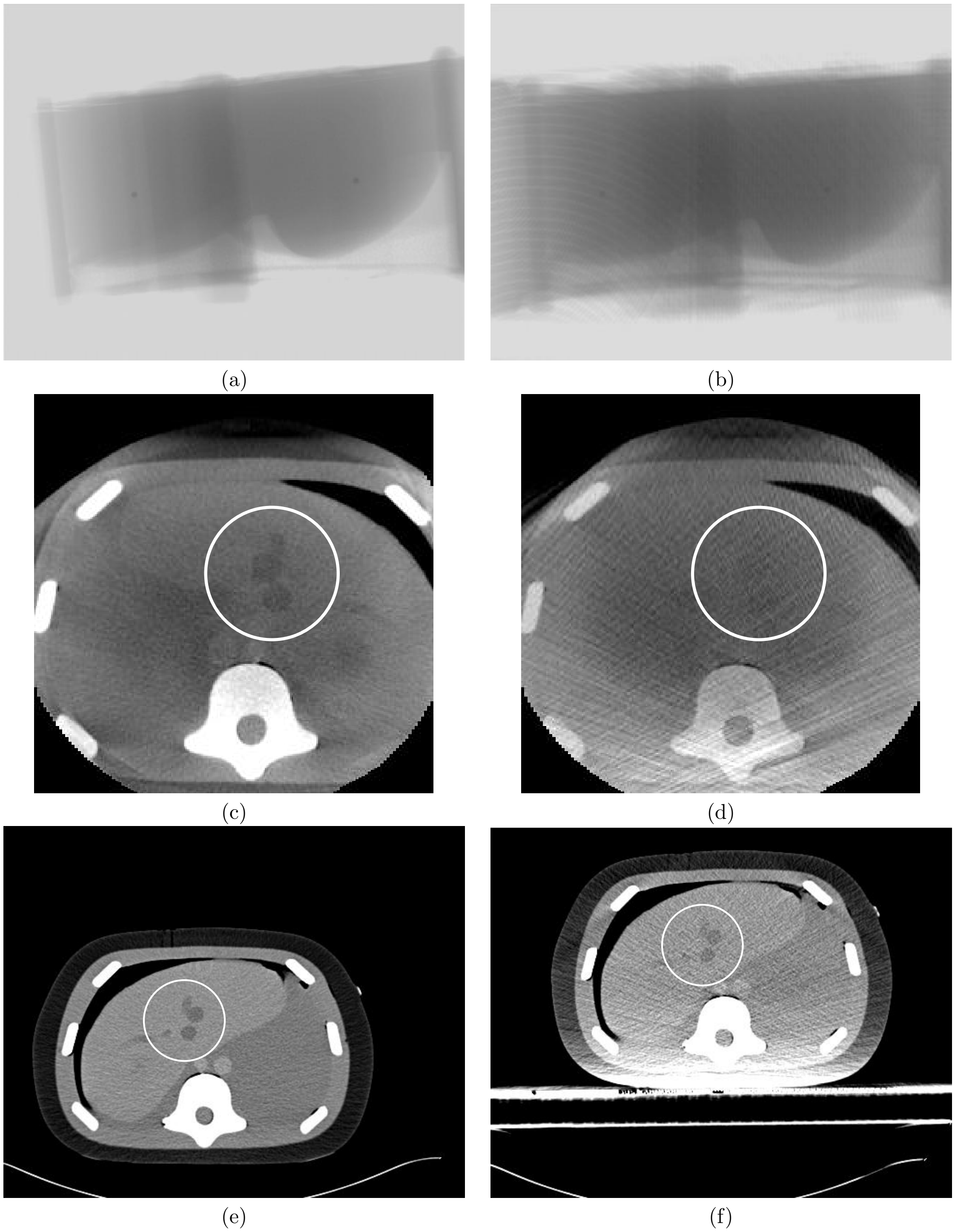


**Figure 4.** Effect of flat-panel field generator on image quality, all images are of the CIRS abdominal phantom. Notice deteriorated image quality in marked regions. (a,b) X-ray projection images without and with field generator. (c,d) Cone-beam CT axial slice without and with field generator. (e,f) CT axial slice without and with field generator. CT-fluoroscopy images were similar to images (e,f).

On the other hand the 3D Guidance with short-range field generator was the worst in terms of stability. That is, measurements fluctuated considerably but when averaged gave excellent accuracy.

| | Aurora | 3D Guidance short-range | 3D Guidance flat-panel |
|---|---|---|---|
| maximal sample distance variability | 0.26 | 4.48 | 0.67 |
| RMS | 1.01 | 0.38 | 0.77 |
| mean | 0.76 | 0.34 | 0.61 |
| standard deviation | 0.67 | 0.18 | 0.48 |
| range | 3.87 | 0.87 | 2.30 |
| max | 3.91 | 0.90 | 2.39 |
| 95 percentile | 2.20 | 0.69 | 1.91 |

**Table 1.** Results of accuracy experiments in interventional radiology suite. All measurements are in millimeters.

In the CT suite there are two primary causes of electromagnetic distortion, the patient couch and the CT gantry. In practice, navigation is performed as far as possible from the CT gantry, so that the couch is the primary cause of distortion. Table 2 summarizes the accuracy evaluation in the CT suite. In this environment the 3D Guidance with flat-panel was the most accurate. Note that the main cause of the distortion is the couch mechanism that is underneath the field generator, which complies with the system's assumptions. The 3D Guidance with short-range field generator and the Aurora system had comparable accuracy.

| | Aurora | 3D Guidance short-range | 3D Guidance flat-panel |
|---|---|---|---|
| maximal sample distance variability | 0.54 | 2.54 | 0.30 |
| RMS | 5.76 | 6.49 | 1.08 |
| mean | 5.14 | 5.67 | 1.02 |
| standard deviation | 2.62 | 3.17 | 0.36 |
| range | 18.33 | 17.34 | 1.76 |
| max | 19.24 | 18.14 | 1.96 |
| 95 percentile | 10.83 | 12.29 | 1.56 |

**Table 2.** Results of accuracy experiments in CT suite. All measurements are in millimeters.

In the pulmonology suite the primary source of distortion is the patient stretcher. In our case we evaluated accuracy with the Hill-Rom (Batesville, Indiana, USA) P8000 transport stretcher. Table 3 summarizes the accuracy evaluation in the pulmonology suite. In this environment the Aurora and 3D Guidance with short-field generator were comparable and more accurate than the 3D Guidance with flat-panel field generator.

| | Aurora | 3D Guidance short-range | 3D Guidance flat-panel |
|---|---|---|---|
| maximal sample distance variability | 0.26 | 1.85 | 2.43 |
| RMS | 1.16 | 1.00 | 3.14 |
| mean | 0.95 | 0.89 | 2.78 |
| standard deviation | 0.67 | 0.45 | 1.46 |
| range | 5.70 | 3.76 | 10.02 |
| max | 5.83 | 3.92 | 10.40 |
| 95 percentile | 2.19 | 1.54 | 5.78 |

**Table 3.** Results of accuracy experiments in pulmonology suite. All measurements are in millimeters.

### 3.3. Robustness

Robustness of the EMTS was evaluated in the CT and interventional radiology suites as described in section 2.7.

In the CT suite when acquiring data far from the gantry the mean(std) distance between the two tracked sensors for the Aurora system was $46.73(0.04)mm$, for the 3D Guidance with flat-panel field generator the mean(std) distance was 55.82(0.10)$mm$ and with the short-range field generator 58.03(0.38)$mm$. We then acquired tracking data during acquisition of a single CT-fluoroscopy image and during a CT scan. For the Aurora system 30% of the data was not reported for the single image case, and 93.4% of the data during the CT scan. Figure 5 summarizes the data acquired using the 3D Guidance system during single image acquisition and during a complete CT scan. Based on these results we conclude that all three systems cannot be used during image acquisition.

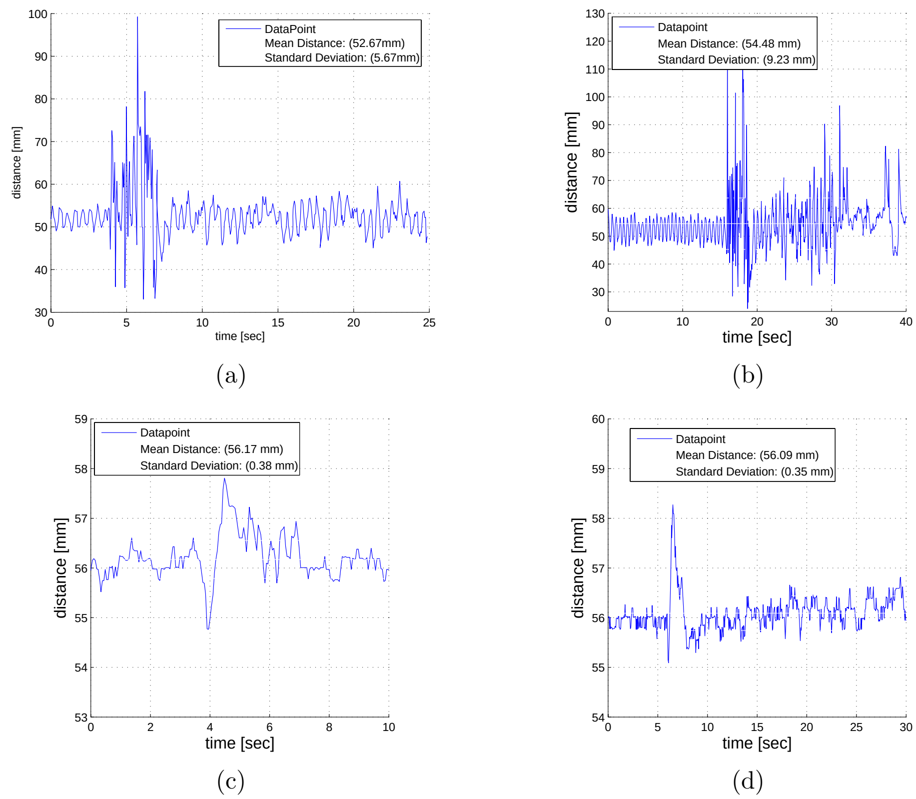



**Figure 5.** Distances between two fixed sensors during single CT-fluoroscopy image acquisition (left column) and during CT scan (right column). (a,b) 3D Guidance with short-range field generator, and (c,d) 3D Guidance with flat-panel field generator.

In the interventional radiology suite when acquiring data with the C-arm away from the tracking location the mean(std) distance between the two tracked sensors for the Aurora system was 21.84(0.06)$mm$, for the 3D Guidance with flat-panel field generator the mean(std) distance was 52.28(0.12)$mm$ and with the short-range field generator 52.63(0.61)$mm$. Note that for each system the distance can be different as the sensors are placed in an arbitrary position. Figure 6 summarizes this experiment, with data for each of the systems as recorded during a single fluorscopic image acquisition and during a rotation of the C-arm for cone-beam CT data acquisition. Based on our results we conclude that the Aurora and 3D Guidance system with short-range field generator should not be used in conjunction with imaging, and the 3D Guidance system with flat-panel field generator can be used during imaging, although it does have a detrimental effect on the images as described above.

## 4. DISCUSSION AND CONCLUSIONS

We have presented a holistic approach to evaluating electromagnetic tracking systems in the clinical environment that takes into account requirements beyond measurement accuracy.

In the past electromagnetic tracking system evaluation has focused on the system's accuracy and ability to deal with the presence of electromagnetic field distorting objects. This type of assessment is insufficient for the

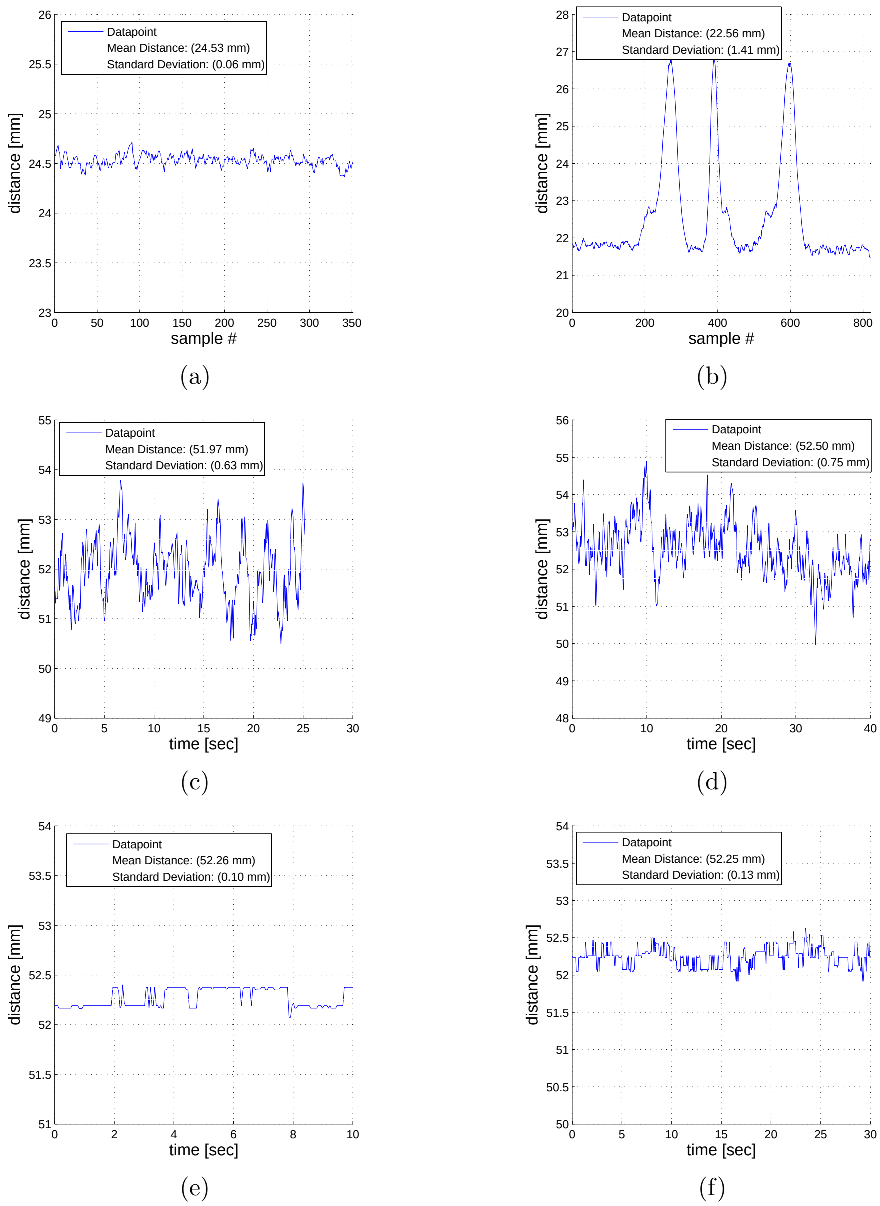



**Figure 6.** Distances between two fixed sensors during single X-ray image acquisition (left column) and during C-arm rotation for cone-beam CT data acquisition (right column). (a,b) Aurora system, (c,d) 3D Guidance with short-range field generator, and (e,f) 3D Guidance with flat-panel field generator.

clinical environment. For example, the 3D Guidance system using the flat-panel configuration was found to be the most accurate in the CT suite environment, but because it is placed underneath the patient it degrades the quality of the CT and CT-fluoroscopy images. Thus if accuracy were the only requirement this would be the system of choice. Given that imaging is at the heart of these interventions it is up to the physician to decide if the quality of the images is sufficient.

Based on our experience using electromagnetic tracking in the clinical environment we have compiled a comprehensive list of requirements. These requirements should be assessed on a per-procedure basis and include, the system's refresh rate, the number of sensors that need to be tracked, the size of the navigated region, system interaction with the environment, can the sensors be embedded into the tools and provide the desired information (5DOF vs. 6DOF), and tracking accuracy and robustness in the specific interventional environment. We assessed the Aurora EMTS, and the 3D Guidance EMTS with short-range and flat-panel field generator configurations using these requirements. Each of the systems was found to have certain strengths and weaknesses, but none of them was optimal across environments and procedures.

## ACKNOWLEDGMENTS

This work was funded by US Army grant W81XWH-04-1-0078. The content of this manuscript does not necessarily reflect the position or policy of the U.S. Government.

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