Review Article

Review paper

Performance and suitability assessment of a real-time 3D electromagnetic needle tracking system for interstitial brachytherapy

Samir Boutaleb, PhD[1,2], Emmanuel Racine, PhD[1,2], Olivier Fillion, MSc[1,2], Antonio Bonillas, BSc[3], Gilion Hautvast, PhD[3], Dirk Binnekamp, BSc[4], Prof. Luc Beaulieu, PhD[1,2]

[1]Département de Radio-Oncologie et Centre de Recherche du CHU de Québec, Québec, Canada, [2]Département de Physique, de Génie Physique et d'Optique et Centre de Recherche sur le Cancer, Université Laval, Québec, Canada, [3]Biomedical Systems, Philips Group Innovation, Eindhoven, The Netherlands, [4]Integrated Clinical Solutions & Marketing, Philips Healthcare, Best, The Netherlands

Abstract

Purpose: Accurate insertion and overall needle positioning are key requirements for effective brachytherapy treatments. This work aims at demonstrating the accuracy performance and the suitability of the Aurora® V1 Planar Field Generator (PFG) electromagnetic tracking system (EMTS) for real-time treatment assistance in interstitial brachytherapy procedures.

Material and methods: The system's performance was characterized in two distinct studies. First, in an environment free of EM disturbance, the boundaries of the detection volume of the EMTS were characterized and a tracking error analysis was performed. Secondly, a distortion analysis was conducted as a means of assessing the tracking accuracy performance of the system in the presence of potential EM disturbance generated by the proximity of standard brachytherapy components.

Results: The tracking accuracy experiments showed that positional errors were typically 2 ± 1 mm in a zone restricted to the first 30 cm of the detection volume. However, at the edges of the detection volume, sensor position errors of up to 16 mm were recorded. On the other hand, orientation errors remained low at ± 2º for most of the measurements. The EM distortion analysis showed that the presence of typical brachytherapy components in vicinity of the EMTS had little influence on tracking accuracy. Position errors of less than 1 mm were recorded with all components except with a metallic arm support, which induced a mean absolute error of approximately 1.4 mm when located 10 cm away from the needle sensor.

Conclusions: The Aurora® V1 PFG EMTS possesses a great potential for real-time treatment assistance in general interstitial brachytherapy. In view of our experimental results, we however recommend that the needle axis remains as parallel as possible to the generator surface during treatment and that the tracking zone be restricted to the first 30 cm from the generator surface.

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Key words: electromagnetic tracking, interstitial brachytherapy, interventional guidance.

Purpose

Electromagnetic tracking systems are versatile devices allowing real-time wireless guidance of tools or other instruments without line-of-sight requirement. Their development has been particularly prominent over the past decade and their use is becoming an increasingly interesting option among clinicians and researchers. The potential advantages that electromagnetic tracking system (EMTS) can bring to the field of image-guided surgery have been recognized [1,2], and their integration to existing medical devices for the development of new treatment or diagnostic procedures is undergoing a rapid evolution.

Electromagnetic tracking system based on alternating current (AC) technology operate by means of precise conversion of electrical signals generated by miniature sensor coils immersed in alternating magnetic fields. The energy of these fields is mostly concentrated in the lower portion of the radio-frequency (RF) spectrum where EM absorption by biological bodies and tissues is low or negligible. The latter property combined with the ease, at which EM

Address for correspondence: Emmanuel Racine, PhD, Département de Physique, de Génie Physique et d'Optique, et Centre de Recherche sur le Cancer, Université Laval, Québec (QC), Canada, 6 Rue McMahon, G1R 3S1 Québec, Canada, Phone: +1 418 558 6824, ✉ e-mail: Emmanuel.Racine.2@ulaval.ca

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sensors can be embedded in surgical tools or other instruments render EMTS particularly well suited for intraoperative interventions requiring a high degree of precision.

Despite their numerous advantages and the current enthusiasm toward their integration, EMTS also have specific limitations and drawbacks. One such limitation is intrinsic to the EM tracking technology itself, namely the minimum practical sizes of sensors and field generators required to ensure proper operation of the systems, as well as the maximum attainable tracking accuracy given the sensitive nature of the conveyed analog signals. Another important limitation of EMTS is their particular sensitivity to EM field distortion, which can be generated by a plurality of sources such as noisy electronic equipment or sizable metallic or ferromagnetic structures. It has been shown that the relative importance of the induced distortion depends on the size, composition, proximity as well as the shape of the considered objects [3-5].

The EMTS considered in this study is the Aurora® V1 Planar Field Generator (PFG) (Northern Digital Inc. [NDI], Waterloo, Canada), which has received considerable attention in the literature. Among others, the first and second generation of system have been characterized in clinical environments with surgery and imaging tables [5-8], coupled with endoscopic tools [9,10], with the presence of typical surgical tools in the operating room [11-14], during image acquisition by computed tomography [15-17] and with ultrasound probes [18]. These studies have evaluated the impact of metallic components and structures generally placed around the characterized measurement volume of the EMTS but not directly inside. However, Haidegzger *et al*. [10] have conducted experiments that included surgical tools located between the sensors and the field generator. It was found that EM distortion in such circumstances is generally not negligible but can be compensated by following a particular measurement protocol using a cubic plexiglass phantom and a standardized evaluation algorithm. Although the findings of this study are of considerable importance from a methodological and technical point of view, a broad assortment of surgical tools was considered with no specially targeted medical application. The aim of the present study is to specifically assess the performance and suitability of the Aurora® V1 PFG in the dedicated case of prostate brachytherapy (permanent or temporary implants).

Prostate brachytherapy is carried out by precise and repeated implantation of needles or catheters in the prostate volume (typically less than 50 cm^3) [19-22]. The operation involves the presence of several metallic elements and electronic devices in the proximity of the treatment zone: needles (or catheters), a brachytherapy template, a transrectal ultrasound (TRUS) transducer and its stabilizing support, an operating table, guiding monitors as well as numerous arm supports. In low-dose-rate (LDR) brachytherapy, the presence of an important number of small seeds (generally 60 to 120) in the prostate volume could also potentially generate EM distortion given that their composition often include conductive metals such as silver. Incorporation of EMTS to current brachytherapy protocols could enhance physician gestures and improve overall treatment quality but in view of the nature of the operation and hardware involved, a suitability and performance assessment of the technology in this particular context proves necessary.

This paper presents a performance evaluation of the Aurora® V1 PFG for RF-guided needle intervention in interstitial brachytherapy. The prostate brachytherapy configuration was specially chosen because of the numerous equipment and components involved. Two different studies were carried out. First, in an environment free of EM disturbance, the boundaries of the detection volume of the EMTS were characterized and a position as well as an orientation error analysis were conducted. It is worth mentioning that numerous studies have already focused their attention on the tracking accuracy performance of Aurora® systems in ideal or quasi ideal EM conditions [7,10,15]. Although similar, our analysis was performed using different hardware, and can serve as a further assessment of the results so far obtained in the literature for this specific EMTS. Secondly, a distortion analysis was conducted by characterizing the position accuracy of the system in the presence of potential EM distortion generated by several types of brachytherapy components placed in vicinity or directly inside of the characterization volume. The latter analysis was meant to specifically assert the suitability of the Aurora® V1 PFG for real-time assistance in practical clinical contexts.

Material and methods

Electromagnetic tracking system and related equipment

The EMTS considered in this study is the Aurora® V1 PFG, which is depicted in Figure 1. It exploits AC technology for magnetic field generation and produces tracking data at a rate of 40 Hz. An independent EM needle from a biopsy introducer set (PHILIPS Percunav™ 18G x 15 cm) containing a standard five degree-of-freedom sensor compatible with the Aurora® system was used as the tracking tool in the two evaluative studies. 3D tracking data (positions and orientations) were recorded and managed via the NDI ToolBox software (v.4:002:006).

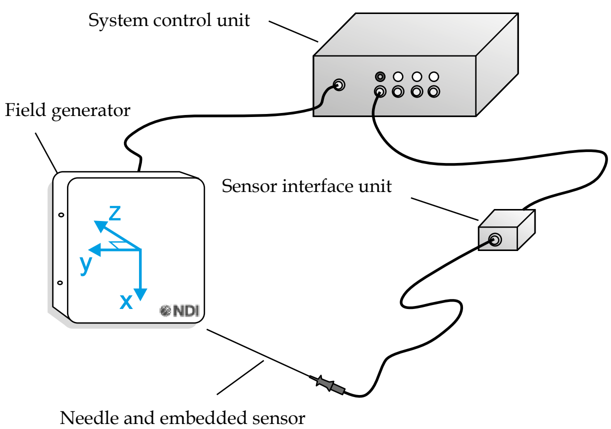


Fig. 1. Simplified representation of the Aurora® V1 electromagnetic tracking system with its corresponding spatial system axis

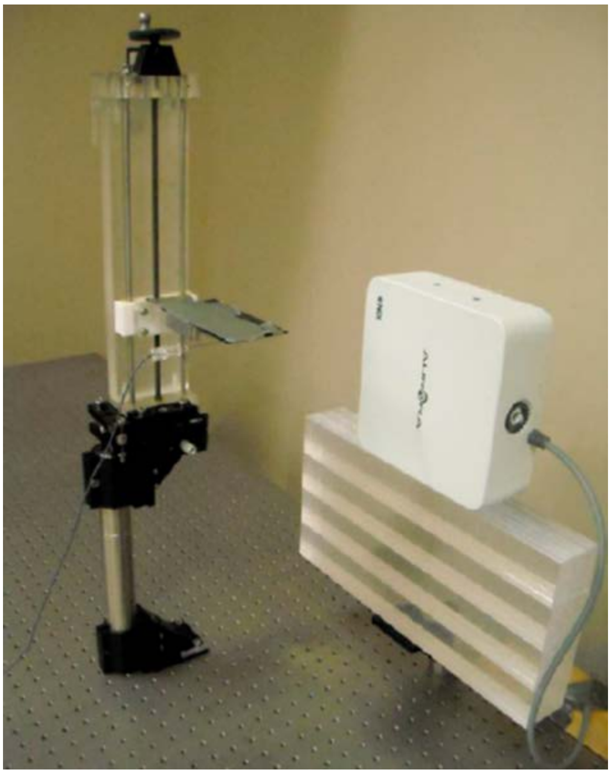


Fig. 2. Experimental setup used for tracking accuracy analysis and characterization of the boundaries of the detection volume. The system *z* axis is perpendicular to the surface of the field generator

Experimental setups

System characterization in an environment free of electromagnetic disturbance

Tracking accuracy analysis and characterization of the boundaries of the detection volume were conducted in an environment free of EM disturbance. The setup used for these experiments is shown in Figure 2. A specially designed mobile needle support was mounted on an optical table, along with a fixed support to maintain the field generator. The needle was solidly maintained on a parallel plastic plate that could be moved vertically by a precise toothed wheel mechanism. At any time, the needle and the field generator were located at least 30 cm above the optical table. The surface of the optical table used is made of stainless steel, which is one of the most likely material to generate EM distortion. Northern Digital Inc., however, specifies that the EMTS can be operated above such a surface provided that the field generator and tracked sensors remain at a distance of at least 30 cm from the latter. This unique setup dampens potential vibrations while providing submillimetric displacement capabilities (± 0.25 mm).

Distortion analysis

The effect of potential EM distortion on the tracking accuracy performance of the EMTS was evaluated using an assortment of brachytherapy tools and components in an arrangement mimicking the configuration of an actual prostate treatment. While a handful of publications report using polycarbonate (PMMA) structures as a basis material for phantoms and other supporting elements, the use of LEGO™ bricks has also been considered as an effective, low cost, and convenient alternative [7,10]. In this study, a combination of both PMMA and LEGO™ bricks was used. A PMMA needle support was initially constructed to mimic the guidance provided by a standard brachytherapy template. This support is comprised of two identical 60 × 60 × 15 mm^3 PMMA pieces perforated by 7 × 7 hole matrices (1.25 mm hole diameter) mounted on a horizontal plate holder (Figures 3B and 3D). It was held in place by a LEGO™ bricks confinement structure positioned on a larger LEGO™ base plate that also served as a solid anchor for the field generator of the Aurora® system (Figure 3D). The confinement structure was designed in such a way as to also act as a holder for an ultrasound probe and allow the height of the PMMA phantom to be adjusted above the latter (Figure 3C). These various components were placed on a wooden table one meter above the floor and ensured that the relative position of the needle in the PMMA phantom with respect to the generator remained constant during experiments.

Acquisition protocols

Characterization of the boundaries of the detection volume

Northern Digital Inc. specifies that the cubic tracking volume of the Aurora® V1 PFG has a side length of 500 mm. However, the NDI ToolBox software allows tracking of tools in a larger 600 × 600 × 600 mm^3 cubic volume in front of the generator. It was hence considered opportune to characterize the boundaries of this larger volume, in which detection of tools by the system is still possible with the NDI software. The characterization was performed by positioning the needle parallel to the z axis of the field generator (perpendicular to the generator surface in Figure 2), and adjusting its position in such a way that the NDI ToolBox software reports its location as being on the edge of the cubic volume. The needle was moved along four edges of the detection volume (those parallel to the system z axis) in 50 mm increments (according to software reporting). A total of 13 tracking measurements per edge were recorded. A representation of the actual shape of the detection volume was then produced with reference needle positions that were recorded by the mobile support at the same time. Linear interpolations between points were later used to render the final shape of the effective detection volume for visualization.

Position and orientation error analysis

Position errors were computed from a total of 486 spatial measurements performed throughout the detection volume (600 × 600 × 600 mm^3). The measurements were taken at every displacement of 50 mm along x, 50 mm along y, and 100 mm along z using the mobile support. Each point was obtained by an average of 40 tracking measurements with a needle orientation perpendicular to the generator surface (Figure 3B).

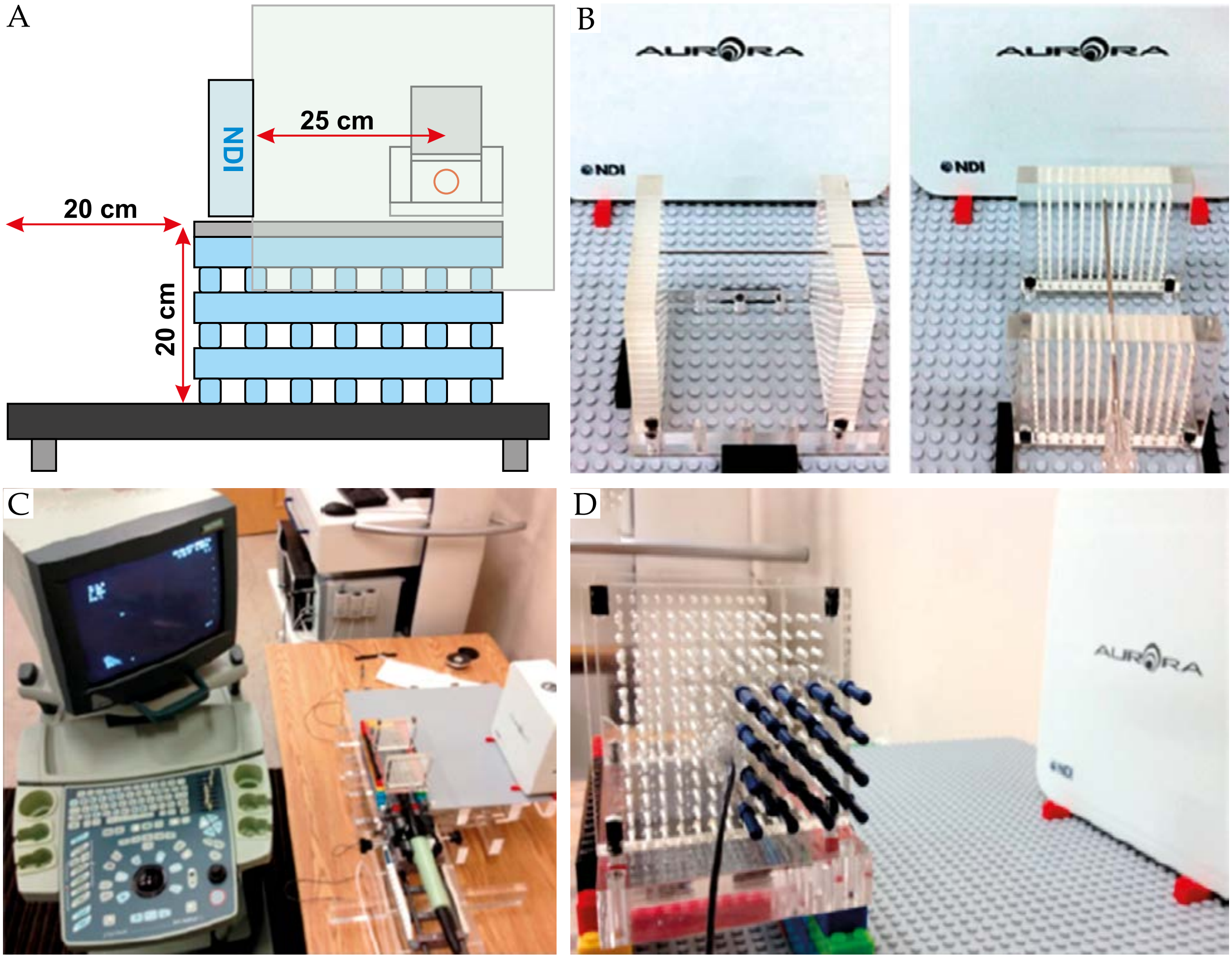


Fig. 3. Experimental setup used for the distortion analysis. **A)** Side view representation of the supporting structures. **B)** PMMA phantom and field generator on the LEGO^{TM} base plate with parallel (left) and perpendicular (right) needle orientations. **C)** Overview of the experimental setup with the CRT monitor, the ultrasound scanner and probe used in the experiment. **D)** Metallic LDR catheters placed around the needle in the PMMA phantom

The orientation error analysis was performed from three distinct experiments. First, an analysis was performed from the measurements used in the position error analysis (since orientation was also recorded). In this case, the needle was held perpendicularly to the generator surface and measurements were taken as described in the previous paragraph. The tracking angle about the *y* axis (Q_y) was recorded and compared to its ideal nil value. Secondly, orientations errors were characterized for three specific needle configurations with respect to the field generator surface: Perpendicular (0º), parallel + (+90º), and parallel (–90º) (Figure 3B). These angles are measured in the *yz* plane of the system with respect to the generator surface. In this experiment, measurements were taken at every tracking displacement of 25 mm along the *z* axis of the generator from *z* = –50 mm to *z* = –575 mm (with *x* = *y* = 0). Finally, orientation error measurements were made with a specially machined PMMA support, which allowed to impose up to 10 predefined needle orientations (Figure 4). The measurements were taken with the needle located at *z* = –55 mm on the system's central axis.

Error analysis for both position and orientation measurements were performed using the basic formula:

$$e = v_{EMTS} - v, \qquad (1)$$

where is a tracking measurement vector (position or orientation) obtained from the EMTS after averaging, and where is the corresponding reference measurement obtained with the needle mobile support.

Distortion analysis

The distortion analysis presented in this paper is directly inspired from the work of Franz *et al*. [23]. It was conducted by characterizing tracking position deviations in a static needle configuration between an undistorted reference measurement (taken in an environment free of EM disturbance), and measurements obtained with the nearby presence of one or several of the following brachytherapy components:

1. A BK-Medical Falcon Type 2101 (B-K Medical ApS, Herlev, Denmark) ultrasound system coupled with a tran-

Fig. 4. Publications report using polycarbonate support used in the orientation accuracy analysis. The support contains machined holes with predefined orientations (± 1°)

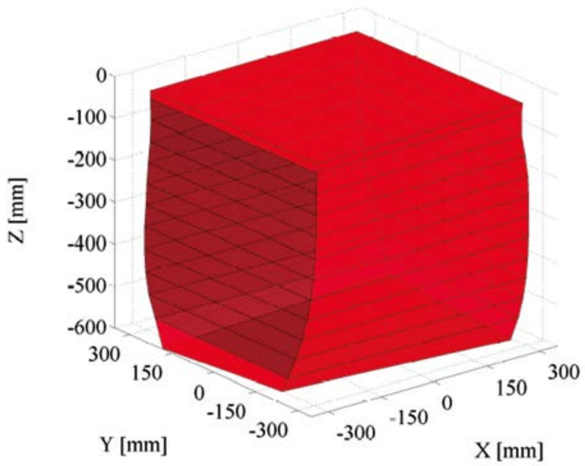


Fig. 5. Characterized boundaries of the detection volume of the Aurora® V1 PFG

srectal ultrasound (TRUS) probe (Bi-Plane Electronic Probe 8658, 5.0-7.5 MHz) (Figure 3C).
2. 20 LDR metallic needles (Nucletron Pre-plugged Needle Set^{TM}) (Nucletron, an Elekta company, Elekta AB, Stockholm, Sweden) surrounding the needle in the PMMA phantom (Figure 3D).
3. A cathode ray tube (CRT) monitor used with the ultrasound scanner and a thin film transistor liquid crystal display (TFT-LCD) monitor such as commonly used for treatment planning.
4. A typical metallic arm used to support surgery trays, monitors or other equipment.

A total of 400 raw tracking measurements (acquisition time of 10 seconds) were taken in each case, and the following computations were carried out:
1. Positional errors. They are defined as the Euclidean distance between the reported needle positions with and without the presence of brachytherapy components. The EM needle was held fixed during all experiments. The geometric mean was also computed and used in a lognormal distribution modeling as commonly done in the literature [11,24,25].
2. Precision. It refers to the jitter, which is defined as the root mean square error (RMSE) of the 400 collected tracking measurements [23].
3. For each measurement, the tracked needle was placed in the dedicated PMMA phantom that was located in the first half of the detection volume. The TRUS transducer was also activated and placed 10 cm below the needle sensor for every distortion measurement so as to simulate the configuration of an actual prostate treatment.

Results

System characterization in an environment free of electromagnetic disturbance

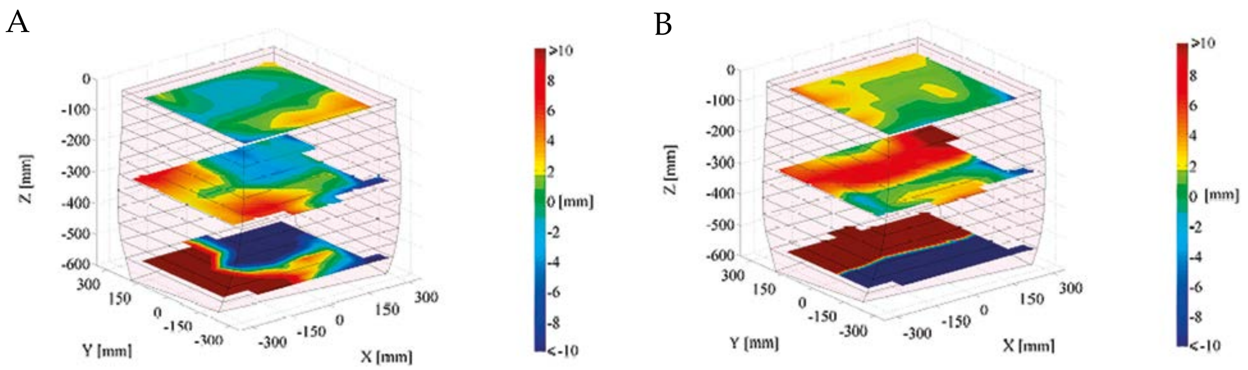
Characterization of the boundaries of the detection volume

Figure 5 displays the actual shape of the detection volume, in which sensors can be tracked by the EMTS. It can be seen that the volume boundaries are not perfectly parallel. The most notable distortion is observed along the y axis, where at one end the volume side length reaches approximately 400 mm (in contrast to the expected 600 mm). A deviation of approximately 30 mm is also observable along the x axis when the volume is viewed from the xz plane.

Positional errors

The three graphs of Figure 6 display the measured positional errors of the EM-tracked needle along the x, y, and z coordinates in three planes located at different distances (z values) from the generator surface. It can be seen that the lowest errors occur in the central region of the plane closest to the generator (z = –50 mm). On the middle plane, important errors of approximately 6 mm are generated near the edges, and even larger ones (up to 10 mm) along the y and z coordinates. The lowest errors are again observed in the central area of that plane. Finally, on the last plane (located at z = –50 mm), positional errors easily reach 10 mm on most of the surface. This observation can be explained by the fact that measurements performed at z = –550 mm are at the very limit of the specified tracking volume of the Aurora® V1 PFG beyond, which tracking accuracy is not guaranteed.

The graphs of Figure 6 offer a qualitative appreciation of the measured positional errors of the EMTS at different distances from the PFG. They were however only obtained from a small subset of the 486 measurements made throughout the detection volume. Figure 7 displays histograms of absolute positional errors (3D) for all data points but located in the specified tracking volume of the Aurora® V1 PFG (a cube of 500 × 500 × 500 mm^3). Errors associated with the first and second halves of the volume are presented. It can be seen that significantly lower positional errors are measured in the first half of the volume. Mean positional errors are respectively 3.4 mm for the first half, and 26 mm for the second one. The largest



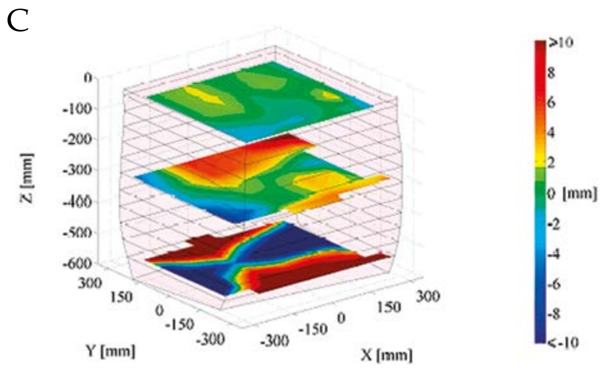


Fig. 6. Needle positional errors measured at distances of 50 mm, 300 mm, and 550 mm from the generator surface. **A), B)** and **C)**: *x*, *y* and *z* coordinates, respectively

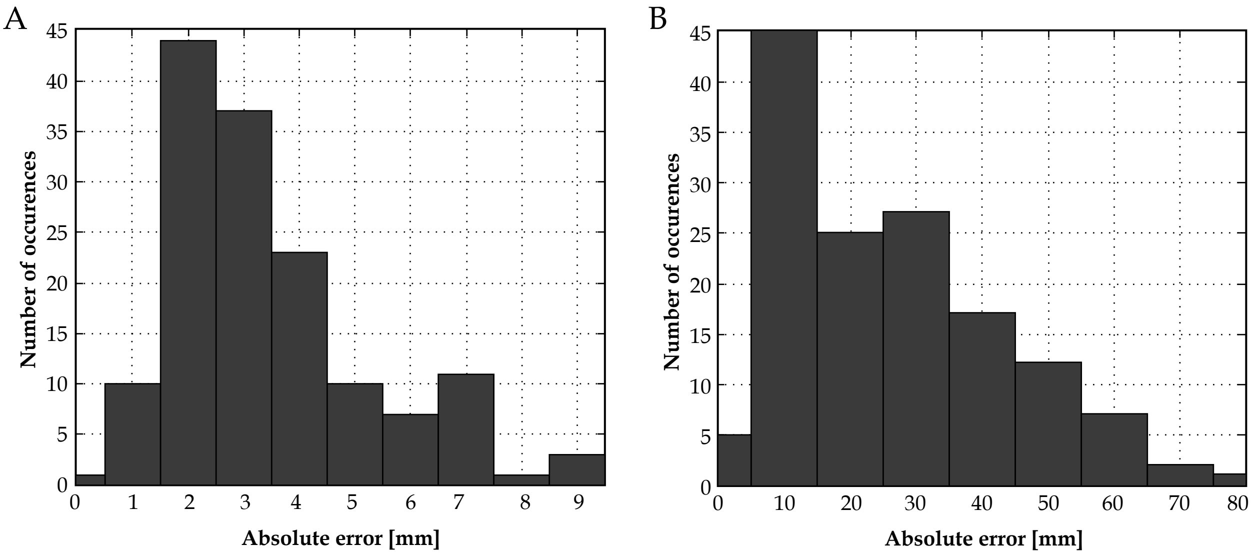


Fig. 7. Histograms of absolute positional errors recorded throughout the specified tracking volume of the Aurora® V1 PFG. **A)** First half ($z \in [-300,-50]$ mm). **B)** Second half ($z \in [-550,-300]$ mm)

errors measured in the second half occur at the farthest distances ($z = -550$ mm) of the PFG, as also illustrated in Figure 6.

Orientation errors

Figure 8 displays the needle tracking orientation errors such as measured from the 486 tracking measurements used for the positional accuracy analysis. It can be seen that the lowest errors are measured in the first plane ($z = -50$ mm), where a maximum absolute deviation of approximately 2° is measured. Relatively low errors are also observed in the second measurement plane ($z = -300$ mm), where the most important angular differences also reach 2°. Orientation errors in the third plane ($z = -550$ mm) are on the other hand much larger, taking values between –10° and +8° due to the far operating distance from the field generator surface.

Figure 9 shows the results of the second characterization experiment where the needle tip was gradually

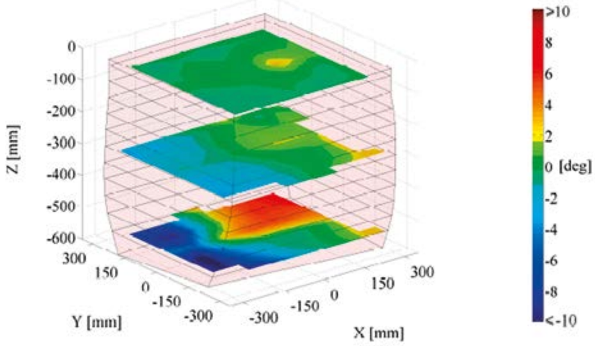


Fig. 8. Needle orientation errors about the y axis of the system measured at distances of 50 mm, 300 mm, and 550 mm from the generator surface

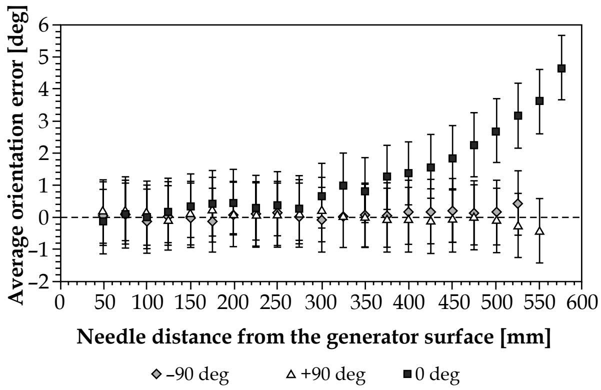


Fig. 9. Needle orientation errors as a function of the needle distance from the generator surface for three distinct needle configurations: Parallel– (–90°), perpendicular (0°), and parallel+ (+90°)

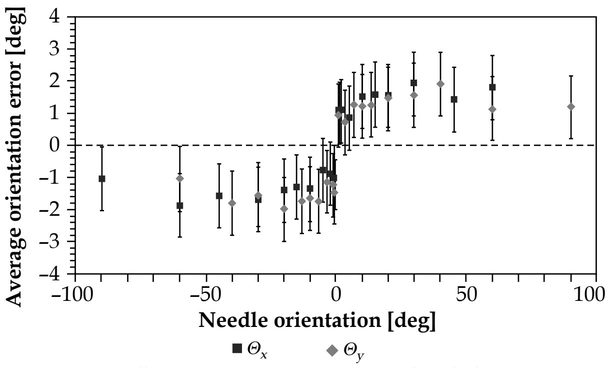


Fig. 10. Needle orientation errors measured with the PMMA support of Figure 4 on system's z axis 55 mm from the generator surface

moved on the z axis of the generator in the perpendicular, parallel +, and parallel– configurations (Figure 3B). It can be seen that the orientation inaccuracies remain particularly low in both parallel configurations, reaching extrema of approximately ± 1° even at the farthest distance from the generator. In the perpendicular configuration, however, orientation errors monotonically increase from 350 mm and over, reaching up to 5° at the far end of the detection volume. This observation is consistent with the results of Figure 8 where orientation errors in the range of 2° to 6° can be observed in the central region of the third plane (z = –550 mm).

Figure 10 displays needle orientation errors measured with the PMMA support of Figure 4. The needle was maintained 55 mm away from the generator surface on the system's z axis. It can be seen that errors of at most 3° are made for all predefined orientations, with slightly lower values around 0°. Although the PMMA support only allows for 10 predefined orientations to be imposed, up to 20 could be obtained by rotating the support and exploiting its lengthwise symmetry. In Figure 10, x and y correspond to the needle orientation angles with respect to the system's x and y axis, respectively.

Distortion analysis

Positional errors

The results of the position error analysis are depicted in Figure 11. For each study case, a tracking reference measurement was first performed without the presence of any equipment, and a mean absolute positional error was computed. The components were then brought into place in vicinity of the EM needle or in periphery of the experimental zone and another measurement was performed. The difference between the two mean errors allowed to quantitatively assert the strength of the EM distortion generated by the considered equipment. It can be seen in Figure 11 that all three reference measurements produced absolute positional errors of approximately 1 mm, which is the result of the intrinsic noise level of the Aurora® EMTS. The presence of a CRT monitor (powered or not) and metallic catheters had virtually no influence on the mean positional error, inducing deviations of at most 0.1 mm from their respective reference values. However, as intuitively predicted, the metallic arm support generated a significant amount of EM distortion. Mean position error differences of approximately 0.5 mm are observed when the arm is located 10 cm away from the needle sensor, and distortion effects are still visible when it is moved further away at 30 cm. These observations are explained by the fact that typical metallic arm supports like the one used in this study are made of stainless steel, which is ferromagnetic in nature and also a relatively good conductor. Therefore, it can easily distorts EM fields. The metallic catheters, on the other hand, caused no important distortion due to their very thin medical grade metal coating.

Positional jitter

The positional jitter was computed from the same raw measurements as those used for the positional error analysis in section III B 1 (400 tracking measurements for each component). Figure 12 shows that the metallic arm supporting the TFT-LCD screen and the metallic cathe-

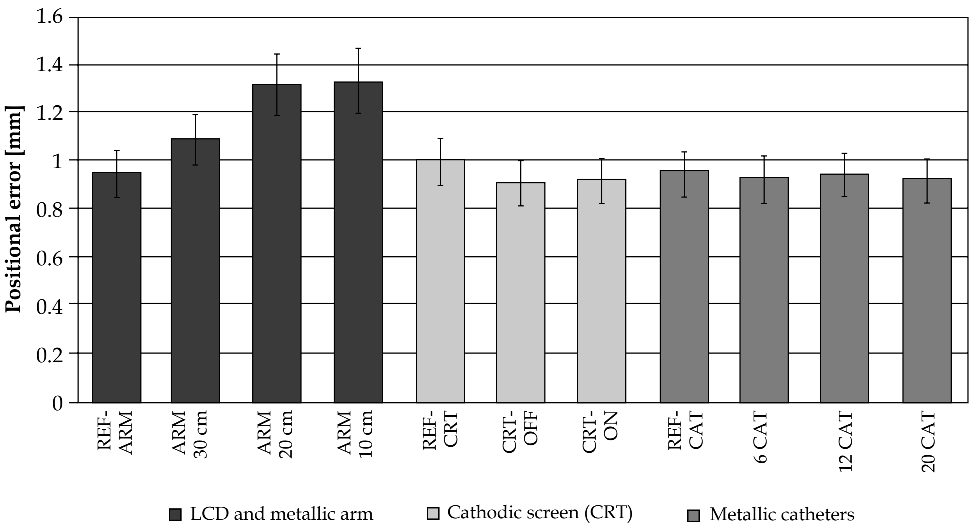


Fig. 11. Static positional tracking error as a function of different types and configurations of brachytherapy equipment with the setup of Figure 3: A TFT-LCD monitor supported by a metallic arm, an active or inactive cathodic screen (CRT) monitor as well as numerous metallic catheters surrounding the electromagnetic needle in the publications report using polycarbonate (PMMA) phantom

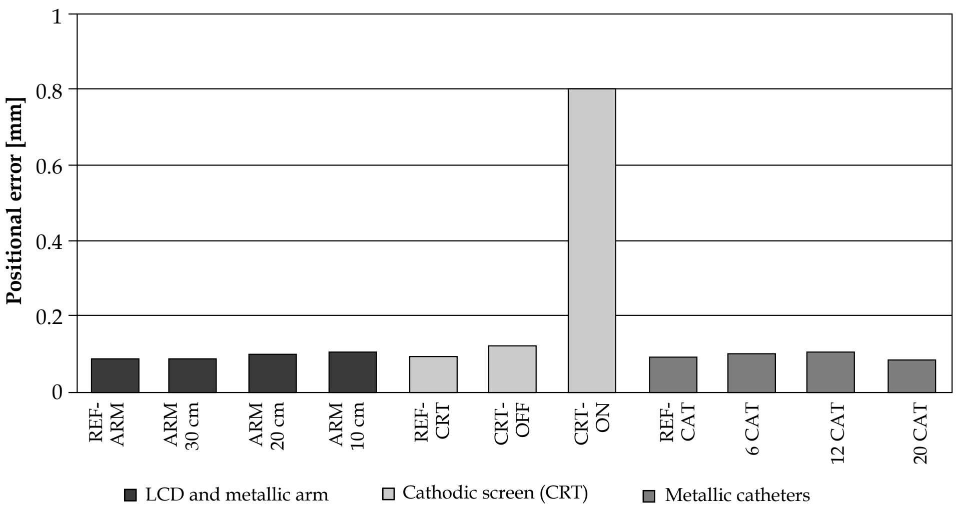


Fig. 12. Positional tracking jitter as a function of different types and configurations of brachytherapy equipment with the setup of Figure 3: A TFT-LCD monitor supported by a metallic arm, an active or inactive cathodic screen (CRT) monitor as well as numerous metallic catheters surrounding the electromagnetic needle in the publications report using polycarbonate (PMMA) phantom

ters produced low jitter values of approximately 0.1 mm. The situation is, however, very different when the CRT monitor was turned ON in proximity of the detection volume, where a jitter increase of a factor of nearly 8 can be observed. This phenomenon is likely caused by the high electric fields generated by the CRT.

Discussion

As mentioned in the introductory section of the paper, numerous studies have already focused their attention on assessing the tracking accuracy performance of the Aurora® V1 PFG. Our work innovates by characterizing the actual shape of the detection volume of the EMTS and evaluating its suitability for potential integration and assistance in general interstitial brachytherapy protocols. The validation was carried out in the specific prostate brachytherapy configuration since it involves the presence of numerous components in vicinity of the treatment zone. Interestingly, the use of EM tracking technologies for assistance in brachytherapy treatments has already been covered in the literature. Recent works for example demonstrate how 3D catheter reconstruction can be conveniently performed using an EMTS [26-28]. Reproducibility assessments of the catheter reconstructions are also presented. Zhou *et al*. [29], on the other hand, had already demonstrated how real-time catheter tracking in high dose rate (HDR) applications can be performed with a 3D guidance system. The EMTS used in their study was the Ascension trakSTAR® EMTS (Ascension Tech. Corp., Milton, VT, USA), which exploits pulsed DC magnetic fields. The Aurora® V1

PFG on the other hand exploits an AC field technology, which is more prone to distortion effects caused by ferromagnetic materials and/or Eddy currents in conductive objects. One important objective of this study was therefore to specifically assert the suitability of this technology for use in general brachytherapy applications, something that had not been previously done in the literature.

Figures 8 and 9 indicate errors of at most 2° are generated in the detection volume up to an operating distance of approximately 30 cm from the generator surface, and of at most 1° when the needle is maintained in a parallel orientation near the central (z) axis of the generator. Overall orientation errors throughout the measurement volume are expected to be significantly lower in this spatial configuration than with the perpendicular orientation. Let us note, however, that interventions with a perpendicular needle orientation in a clinical environment are less likely to be encountered as the generator would need to be positioned parallel to the patient's transverse plane, within his body (in the case of prostate brachytherapy).

Results of the position error analysis in Figure 6 demonstrate the potency of the Aurora® V1 PFG but also highlight some of its limitations, namely with respect to the tracking of sensors located close to the limits of the detection volume. Large positional errors of more than 5 mm can be observed in the two first measurement planes (z = –50 mm and z = –300 mm), especially in the peripheral regions of the latter. Positional errors remain, however, low near the central axis of the generator at a distance less than 300 mm from its surface. It is important to recall that both position and orientation error analysis were performed in the full 600 × 600 × 600 mm^3 detection volume of the EMTS, whereas the recommended tracking volume specified by NDI consists of a 500 × 500 × 500 mm^3 cube centered on the z axis of the generator and located 50 mm above its surface. Important discrepancies between actual and reported tracking measurements could therefore be expected at the edges of the detection volume. Such errors are also the cause of the volume distortion observed in Figure 5. The study allowed to confirm that the edges of the smaller and recommended 500 × 500 × 500 mm^3 tracking volume remain mostly undistorted.

In the second part of the study, results of the distortion analysis in Figures 11 and 12 show that most of the considered brachytherapy components induce negligible EM distortion in vicinity of the needle sensor or the field generator. Only the metallic arm support was found to generate an appreciable amount of distortion causing tracking position error differences of up to 0.5 mm. This observation is consistent with the results of previous publications [5,30,31], and emphasizes the importance of using medical-grade stainless steel or equivalent EM-compatible alloys in the composition of tools used for treatments assisted by EMTS. Another important finding of our study is the relatively important effect on the positional jitter of the presence of an active CRT monitor in vicinity of the detection volume. This observation is in line with the findings of Schnabel *et al*. [32], which describe the adverse effects of nearby computer monitors on tracking accuracy performance of EMTS.

It is furthermore worth to point out that the BK-Medical TRUS probe used in our distortion analysis had no apparent effect on tracking measurements. This observation is in line with the results of Hastenteufel *et al*. [18], who found that 3D US probes could a source of significant EM distortion compared to 2D ones. This latter aspect is of considerable importance as the synergy between EMTS and US guidance is viewed as an increasingly promising contribution to intra-operative treatments requiring a high degree of precision. It is from this very perspective that NDI recently introduced its new Compact Field Generator, which is intended to be directly mounted on a US probe. An initial tracking accuracy assessment of this new system has been done by Franz *et al*. [23], where six different US probes from three different vendors were tested. None of them was found to have an adverse effect on tracking accuracy.

Let us finally note that among the set of brachytherapy components used in the distortion analysis, no operating table or leg stirrups were considered. This is simply because various types of such equipment exist on the market, and that our conclusions would have been valid only for the specific models used in the experiment. Moreover, the actual EM distortion generated by such components would have depended on their spatial configuration with respect to the treatment zone and the field generator, which may vary from one clinical environment to another. For these reasons, we preferred to consider components that are likely to be found in every clinical environment such as metallic needles, arm supports, LCD monitors, etc. The reader is invited to read [26] for EM tracked measurements performed in operating room (OR) conditions including a table and leg stirrups.

Conclusions

This paper presented a performance evaluation of the Aurora® V1 PFG as an effective tool for use in general interstitial brachytherapy. Overall, the results of our study show that the Aurora® V1 PFG provides sufficient tracking accuracy for potential integration in current brachytherapy protocols. However, our study also highlighted some of the main limitations of the system, namely with respect to the range at which tools can be accurately tracked, and in relation to the type of equipment likely to generate significant EM distortion. In view of such limitations, we recommend that the needle remains in the first half of the detection volume during the treatment, preferably in a region centered along the z axis of the generator, and with an orientation parallel to the latter. We also recommend that any tool or accessory located at less than 30 cm from the needle or the field generator be electromagnetically compatible. Additionally, we suggest that the use of CRT monitors for treatment assistance, although nowadays unlikely, be avoided.

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References

1. Baszyński M, Moroń Z, Tewel N. Electromagnetic navigation in medicine-basic issues, advantages and shortcomings, prospects of improvement. *J Phys Conf Series* 2010; 238: 012056.
2. Peters T, Cleary K. Image-Guided interventions: technology and applications. Springer, 2008. [Online]. http://books.google.ca/books?id=ObBiGIXqstgC
3. Stevens F, Conditt MA, Kulkarni N et al. Minimizing electromagnetic interference from surgical instruments on electromagnetic surgical navigation. *Clin Orthop Rel Res* 2010; 468: 2244-2250.
4. Nixon MA, McCallum BC, Fright WR et al. The effects of metals and interfering fields on electromagnetic trackers. *Presence: Teleoper Virt Envir* 1998; 7: 204-218.
5. Kirsch SR, Schilling Ch, Brunner G. Assessment of metallic distortions of an electromagnetic tracking system. *IEEE Trans Med Imaging* 2006: 61410J.
6. Wilson E, Yaniv Z, Zhang H et al. A hardware and software protocol for the evaluation of electromagnetic tracker accuracy in the clinical environment: A multi-center study. *IEEE Trans Med Imaging* 2007: 65092T1.
7. Nafis C, Jensen V, Von Jako R. Method for evaluating compatibility of commercial electromagnetic (EM) microsensor tracking systems with surgical and imaging tables. *IEEE Trans Med Imaging* 2008: 691820.
8. Yaniv Z, Wilson E, Lindisch D et al. Electromagnetic tracking in the clinical environment. *Med Phys* 2009; 36: 876-892.
9. Ching LY, Moller K, Suthakorn J. Non-radiological colonoscope tracking image guided colonoscopy using commercially available electromagnetic tracking system. IEEE Conference on Robotics Automation and Mechatronics (RAM) 2010; 62-67.
10. Haidegzger T, Sirokai B, Fenyvesi G et al. Repeatable assessment protocol for electromagnetic trackers. *IEEE Trans Med Imaging* 2012: 83161S.
11. Wilson E, Slack R, Banovac F et al. Electromagnetic tracker accuracy in the cyberKnife suite. *IEEE Trans Med Imaging* 2006: 61411R.
12. Zhang H, Banovac F, Lin R et al. Electromagnetic tracking for abdominal interventions in computer aided surgery. *Comput Aided Surg* 2006; 11: 127-136.
13. Bø LE, Leira HO, Tangen GA et al. Accuracy of electromagnetic tracking with a prototype field generator in an interventional OR setting. *Med Phys* 2012; 39: 399-406.
14. Franz A, Servatius M, Seitel A et al. Navigated targeting of liver lesions: Pitfalls of electromagnetic tracking. *Biomed Eng* 2012; 57(SI-1 Track-C): 897-900.
15. Maier-Hein L, Franz A, Birkfellner W et al. Standardized assessment of new electromagnetic field generators in an interventional radiology setting. *Med Phys* 2012; 39: 3424-3434.
16. Shen E, Shechter G, Kruecker J et al. Effects of sensor orientation on AC electromagnetic tracking system accuracy in a CT scanner environment. *IEEE Trans Med Imaging* 2008; 691823.
17. Gergel I, Gaa J, Müller M et al. A novel fully automatic system for the evaluation of electromagnetic tracker. *IEEE Trans Med Imaging* 2012; 831608.
18. Hastenteufel M, Vetter M, Meinzer HP et al. Effect of 3D ultrasound probes on the accuracy of electromagnetic tracking systems. *Ultrasound Med Biol* 2006; 32: 1359-1368.
19. Hoskin PJ, Colombo A, Henry A et al. GEC/ESTRO Recommendations on high dose rate afterloading brachytherapy for localized prostate cancer: an update. *Radiother Oncol* 2013; 107: 325-332.
20. Kovács G, Pötter R, Loch T et al. GEC/ESTRO-EAU Recommendations on temporary brachytherapy using stepping sources for localized prostate cancer. *Radiother Oncol* 2005; 74: 137-148.
21. Davis BJ, Horwitz EM, Lee WR et al. American brachytherapy society consensus guidelines for transrectal ultrasound-guided permanent prostate brachytherapy. *Brachytherapy* 2012; 11: 6-19.
22. Yamada Y, Rogers L, Demanes DJ et al. American brachytherapy society consensus guidelines for high-dose-rate prostate brachytherapy. *Brachytherapy* 2012; 11: 20-32.
23. Franz AM, März K, Hummel J et al. Electromagnetic tracking for US-guided interventions: Standardized assessment of a new compact field generator. *Int J Comput Assist Radiol Surg* 2012; 7: 813-818.
24. Kindratenko VV. A Survey of electromagnetic position tracker calibration techniques. *Virt Real* 2000; 5: 169-182.
25. Frantz DD, Wiles A, Leis S et al. Accuracy assessment protocols for electromagnetic tracking systems. *Phys Med Biol* 2003; 48: 2241.
26. Bharat S, Kung C, Dehghan E et al. Electromagnetic tracking for catheter reconstruction in ultrasound-guided high-dose-rate brachytherapy of the prostate. *Brachytherapy* 2014; 13: 640-650.
27. Poulin É, Racine E, Binnekamp D et al. Fast, automatic, and accurate catheter reconstruction in HDR brachytherapy using an electromagnetic 3D tracking system. *Med Phys* 2015; 42: 1227-1232.
28. Damato A, Bhagwat M, Buzurovic I et al. Catheter digitization in high-dose-rate brachytherapy with the assistance of an electromagnetic (EM) tracking system. *Med Phys* 2014; 41: 487-488.
29. Zhou J, Sebastian E, Mangona V et al. Real-time catheter tracking for high-dose-rate prostate brachytherapy using an electromagnetic 3D-guidance device: a preliminary performance study. *Med Phys* 2013; 40: 021716.
30. Hummel J, Figl M, Birkfellner W et al. Evaluation of a new electromagnetic tracking system using a standardized assessment protocol. *Phys Med Biol* 2006; 51: N205-10.
31. Nafis C, Jensen V, Beauregard L et al. Method for estimating dynamic EM tracking accuracy of surgical navigation tools. *IEEE Trans Med Imaging* 2006: 61410K.
32. Schnabel UH, Hegenloh M, Müller HJ et al. Electromagnetic tracking of motion in the proximity of computer generated graphical stimuli: A tutorial. *Behav Res Meth* 2013; 45: 696-701.