Electromagnetic tracking for treatment verification in interstitial brachytherapy

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Abstract

Electromagnetic tracking (EMT) is used in several medical fields to determine the position and orientation of dedicated sensors, e.g., attached to surgical tools. Recently, EMT has been introduced to brachytherapy for implant reconstruction and error detection. The manuscript briefly summarizes the main issues of EMT and error detection in brachytherapy. The potential and complementarity of EMT as treatment verification technology will be discussed in relation to *in vivo* dosimetry and imaging.

Purpose

Interstitial brachytherapy (IBT) is a treatment option for a variety of tumor sites including, e.g., prostate [1], head and neck [2], breast [3], and gynecology [4]. Implantation of the needles/catheters (without loss of generality, all different types of needles or catheters will be referred to as *catheters* in this article, unless a differentiation is required) is patient specific and requires imaging such as computed tomography (CT), magnetic resonance imaging (MRI), transrectal ultrasound (TRUS), or conventional X-rays to determine the track of each implanted catheter, the so-called implant geometry. Often, this procedure is carried out manually, i.e., by identifying the trace of each catheter in the image data as part of treatment planning. As in any treatment modality, also IBT underlies the risk of errors and uncertainties. Imaging artefacts, limited resolution of the imaging data, and close proximity/overlap of the (projected) implant can deteriorate the reconstruction result with discrepancies of up to 5.5 mm [5,6] or even errors in catheter identification. A number of reports have been published on brachytherapy errors by international bodies including the International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA), and the GEC-ESTRO [5,7,8]. In addition, a number of databases exist that collect specific errors or events. Among them is the collection of the Nuclear Regulatory Commission (NRC) in the United States (US) [9].

During treatment plan optimization, dwell positions and dwell times are determined based on the reconstructed implant fulfilling the clinical criteria for target volumes and organs at risk (OAR). The treatment plan is electronically transferred to the afterloader control unit. Before treatment administration, patient specific quality assurance steps such as verification of the source position for a number of the channels is carried out in addition to non-patient quality assurance checking. Treatment is applied as pulsed-dose-rate (PDR) or high-dose-rate (HDR) IBT with different fractionation schedules. In current clinical practice, a single treatment plan may be optimized and used for each treatment fraction, or the same treatment plan may be used for several fractions delivered based on the same implant.

One recently investigated option to detect errors or quantify the uncertainties in IBT is electromagnetic tracking (EMT). Since many years, EMT is used in various medical applications including EM navigated punctures [10,11], cardiac mapping [12], or external beam radiation therapy [13]. Based on the generation of a precisely defined magnetic field, such systems quantify position and orientation of small dedicated sensors in the field. Recent reviews are provided by Franz *et al*. [14] for a broad introduction and Zhou *et al*. [15] with respect to EMT application in brachytherapy.

The purpose of this manuscript is to introduce the concept of treatment verification by EMT for IBT. Due to the novelty of that application, clinical data are scarce and the content will thus enlighten phantom studies and future potential of the technique.

Error and uncertainty classification

Deviations from the intended treatment outcome can be the results of errors or uncertainties. According to the Insti-

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tute of Medicine in the US, errors are defined as "the failure of planned action to be completed as intended (i.e., error of execution) or the use of a wrong plan to achieve an aim (i.e., error of planning)" [16] while uncertainty "is a parameter that characterizes the dispersion of values that can be obtained for a particular measurement when it is performed repeatedly" [17]. In principle, errors can be prevented, while uncertainties cannot be eliminated, although their magnitude may be reduced. Errors can be due to human mistakes or machine failures. In brachytherapy, errors are mainly human-caused with typical examples being "failure to identify the patient properly", wrong specification of source positions, or specifying dwell positions in the reverse order [7]. Also, the NRC lists human errors such as wrong indexer length, catheter reconstruction errors, misidentified first dwell positions, and inverted catheter direction as the most frequent errors reported in 2005-2013 [18,19]. Other potential errors include swap of catheters during reconstruction or afterloader connection, wrong intersections during implant reconstruction, or usage of wrong transfer tubes.

Influence and extent of uncertainties were recently reviewed by Kirisits *et al.* [5]. Among them are dosimetric influences such as source strength or limitations in the dose calculation engine (e.g., AAPM TG-43 [20,21] based algorithms ignoring heterogeneous tissues and applicator materials), but also variations in implant geometry due to moving organs, tissue swelling, or shifts of individual catheters or the whole implant.

Among the intensively discussed options to prevent errors and to minimize uncertainties are *in vivo* dosimetry (IVD) and imaging, ideally performed in real-time during treatment delivery [22,23]. Tanderup *et al.* reviewed the use of IVD and projected the current developments into the near future [22]. Table 1 lists the most important errors and variations of brachytherapy along with the potential for IVD. Kertzscher *et al.* [23] and also Tanderup and Kertzscher [19] extended this table to include the potential of real-time imaging. The main findings of Table 2 in Ref. [23] are reproduced in Table 1. Only the combination of IVD and imaging is able to detect all listed errors since patient identification is not feasible by IVD. Imaging is the method of choice for direct determination of organ motion related changes and variations in the implant position or geometry. As reported below, the motivation of some of the current investigations of EMT application in IBT is the potential of EMT to act as a complementary technique to IVD and imaging for the detection of errors and variations in IBT.

Implementation of electromagnetic tracking in brachytherapy

Electromagnetic tracking is implemented in various technical options and by several vendors [14]. Generally, the systems consist of a field generator (FG) that houses a set of coils producing in an alternating manner at least

Table 1. Errors and variations in brachytherapy along with the potential of detectability by real-time *in vivo* dosimetry (IVD), real-time imaging (each according to [19,22,23]), and real-time electromagnetic tracking (EMT). The probability of error and the potential effect were reported by Kertzscher *et al.* [23], i.e. only the classification of detectability by real-time EMT and the needed EMT coordinate systems is original in this manuscript. The EMT coordinate systems refer to: «E», the intrinsic coordinate system of the EMT device; «F» fiducial markers visible in imaging and EMT reproducibly placed during each treatment fraction; «A» an absolute cross-calibration between EMT and imaging as, e.g., reported by Bharat *et al.* for transrectal ultrasound and EMT [24]. A schematic drawing of the coordinate system options is shown in Figure 2. (✓) refers to partially applicable

| Quality item	Detectability			EMT coordinate system	Error probability and effect [23]	
	IVD	Imaging	EMT		Probability of error	Effect
Source calibration	✓	✗	✗	–	Low	Low-high
Afterloader source positioning and dwell time (non-patient specific)	✓	✗	(✓)	E	–	–
Afterloader malfunction	✓	✗	(✓)	E	Low	Low-high
Patient identification	✗	✓	(✓)	E/F	Low	High
Correct treatment plan	✓	✗	✓	E	Low	High
Intra- and interfraction organ/applicator movement	✓	✓	✓	E/F/A	–	–
Applicator reconstruction	✓	✓	✓	E	Intermediate	Low-intermediate
Applicator length/source indexer length	✓	✗	✓	E/F	Intermediate	Low-high
Source step size (patient specific)	✓	✗	✓	E	Low	High
Interchanged guide tubes	✓	✗	✓	E/F	Intermediate	Low-high
Recording of dose	✓	✗	✗	–	–	–
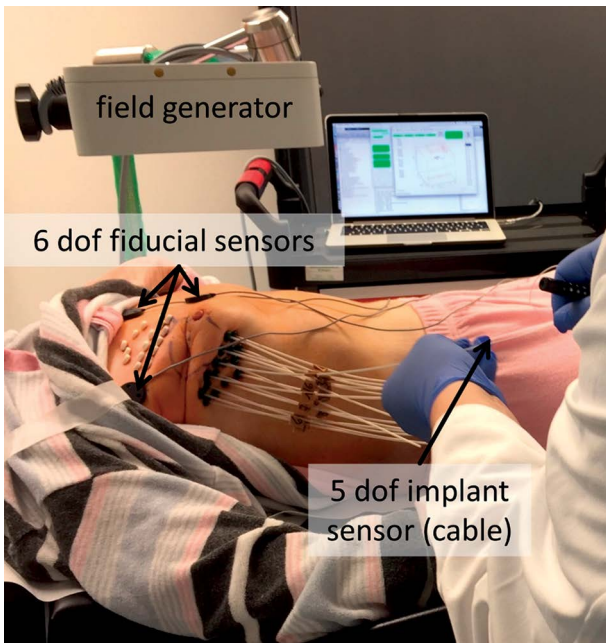
Fig. 1. Clinical use of the electromagnetic tracking system Aurora (NDI, Waterloo, Canada). The field generator spans the cubic measurement volume, in which the position and orientation of small sensors can be determined. In this example, a 5 degree of freedom (DOF) implant sensor is used to quantify the geometry of an interstitial brachytherapy breast implant. Three 6DOF fiducial sensors attached to the chest generate a reference coordinate system (method «F» in Table 1)

three precisely defined, inhomogeneous magnetic fields. The fields span a typical tracking volume of 500 x 500 x 500 mm^3 being the specification of the NDI (Waterloo, Canada) planar FG shown in Figure 1, which is used for most of the studies at Universitätsklinikum (UK) Erlangen. The magnetic field can, e.g., be measured by inductors that determine the gradient of the field at a specific point, i.e. the magnetic flux. Time-resolved measurements at 40-250 Hz are common for medical EMT [14] in 5 degrees of freedom (DOF) using a single 5DOF sensor (three degrees for position and two degrees for rotation), 6DOF sensors are feasible by combining two 5DOF sensors typically requiring a larger housing.

Sensors with 5DOF are sufficiently small (0.9-1.3 mm in diameter [15]) for insertion into typical catheters used

for IBT. As reviewed by Zhou *et al.*, several groups recently started to explore the potential using EMT systems from different vendors for brachytherapy [15]. The systems reach an accuracy of < 0.9 mm if used in environments free of disturbances such as metals that allow eddy currents disturbing the electromagnetic field. Currently, EMT is used in feasibility studies based on phantoms typically with the goal of implant definition [24,25,26] or quality assurance [27,28]. Bharat *et al.* focused on prostate treatments and showed that EMT can be combined with TRUS not only "mechanically" with respect to system setup, but also regarding the measurement of coordinate systems. Electromagnetic tracking-based applicator reconstruction could therefore be easily overlaid with TRUS imaging data. Feasibility of clinical integration is currently showing at UK Erlangen where the geometry of breast implants is determined by EMT prior the irradiation in each fraction in a study approved by the institutional review board [29]. The FG is mounted on a mobile stand with a flexible arm that can quickly be positioned next to the patient in the HDR treatment room (see Figure 1). The catheters of the implant are sequentially tracked by manual insertion of a 5DOF sensor. Catheter implants of more than 30 patients have been already measured at UK Erlangen throughout their fractionated HDR-IBT treatment including measurements in the CT room.

Electromagnetic tracking-determined positions are related to the position of the typically mobile FG (coordinate system labeled «E» in Table 1 and Figure 2). In addition, EMT only "sees" sensors but does not image the patient's anatomy. A full quantitative integration of EMT with the coordinate systems used in IBT, thus requires cross-calibration of the EMT and the coordinate system of the imaging device used for specification of treatment volumes, OAR, and dwell positions. This task can be adequately achieved by identifying at least three landmarks visible in both, EMT and imaging, coordinate systems, e.g., by a reference EMT sensor attached to the stepper of the TRUS in prostate treatments in combination with probing positions with EMT-tracked needles that are visible in the TRUS data [24]. A seamless transition between the two unified coordinate systems (labeled «A» in Table 1 and Figure 2) is thus feasible, allowing, e.g., for quick and accurate implant reconstruction and overlay with segmented organs. Such co-registrations are not feasible over several days (e.g., for the treatment planning CT and EMT during each treatment fraction) unless multiple and sta-
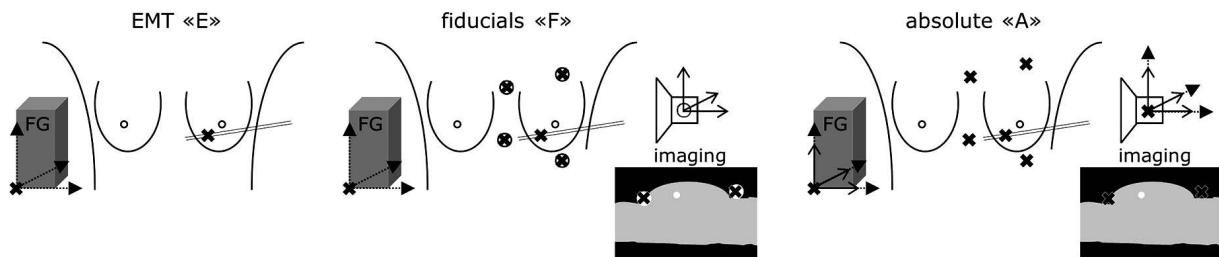

Fig. 2. Schematic of electromagnetic tracking usage in breast cancer treatments. Electromagnetic tracking can either be used standalone (×, method «E»), in combination with fiducials visible in electromagnetic tracking and an alternative imaging system (⊗, method «F»), or fully integrated to an imaging modality by an absolute cross-calibration (method «A»)

ble anatomical landmarks are available at the treatment site. An option would be fiducial EMT sensors placed on the skin (see Figure 1) that allow a correlation between CT imaging and each EMT measurement. The accuracy of that method (labeled «F» in Table 1 and Figure 2) is substantially influenced by the repositioning accuracy of the fiducial sensors and uncertainties due to skin motion.

Potential of electromagnetic tracking for error detection in interstitial brachytherapy

Table 1 lists the most important errors and variations as reported by Tanderup et al. and Kertzscher et al. [19,23]. In addition to error detection by IVD and imaging as proposed by those authors, the table in the current version also lists the potential of error detection by EMT for each quality item. This judgment is not yet proven clinically, but the following paragraphs will motivate why EMT could play the indicated role.

Source calibration/recording of dose

Obviously, EMT cannot be used for dose assessment as the method determines position and orientation only.

Afterloader source positioning and dwell time (non-patient specific)

In principle, one could couple an EMT sensor with the source cable of an afterloader. Then, a fixed connection would be established between source position and EMT-determined position. Since EMT allows high frequent position determination, dwell times could also be measured. Despite high dose levels close to the EMT sensor, a reliable and accurate position reading can be expected from the EMT system [13,30]. As an alternative solution, the EMT sensor could be mounted to the check-cable of the afterloader. As EMT cannot detect dose, decoupling of the source from the cable could not be detected. As reported already by Tanderup et al. [22], the need for new QA options for that task is of minor importance.

Afterloader malfunction

As with the previous item, most of the potential malfunctions of the afterloader (mechanical issues, software failures, but not dosimetric properties) could be detected by EMT.

Patient identification/correct treatment plan/ source step size (patient specific)

In IBT, the catheter implant of the patient is individual regarding the implant geometry and the arrangement of dwell positions and times. Electromagnetic tracking applied just before treatment application, either by manual insertion, as performed at UK Erlangen for geometry assessments of breast implants [29], or by an automatic run of the check-cable with integrated EMT sensor of an afterloader, can determine the patient-specific implant geometry including dwell positions and dwell times. A cor-

rect dosimetric outcome of the treatment plan cannot be measured, but the EMT-determined positions could be the basis for daily dose calculations. The advantage over IVD is the detection prior to application of the treatment.

Intra- and interfraction organ/applicator movement

Movement of individual catheters can be assessed by comparison to the reference implant geometry from treatment planning. Changes of the whole implant, e.g., due to swelling or other post-implant reactions, can be determined similarly. The EMT coordinate system «E» is sufficient. Relative motion of the implant site, e.g., motion of the breast/prostate relative to important OAR could be tracked relative to EMT fiducials (method «F»).

Applicator reconstruction/interchanged guide tubes

Applicator reconstruction can in principle be performed by EMT [24,25,26]. Without matching the coordinate systems, EMT determined implant geometries could be used as applicator/implant libraries [31] for manual overlay with the imaging data. If coordinate systems are matched (method «A») as proposed previously [24,32], the EMT determined geometry can be used directly for automatic applicator/implant placement. Potentially, EMT-based reconstruction is less prone to errors than manual reconstruction – further research is required. In case of manual reconstruction, EMT is a viable option for error detection as shown by Damato et al. with respect to mixing and interchange/swap of catheter traces [27]. Also for this quality item, EMT would spot potential errors prior to treatment delivery.

Applicator length/source indexer (channel) length

Shifts of individual catheters can be determined by EMT-only («E») as a relative shift against the remaining catheters of the implant. Multiple individual shifts or global shifts of the whole implant can also be detected by EMT, but most likely require fiducial sensors as a reference («F»). In phantom studies, Damato et al. showed a specificity and sensitivity of each 100% for individual shifts > 2.7 mm [27].

Conclusions

Electromagnetic tracking is a promising option for error detection, assessment of uncertainties, and implant definition in IBT. Currently, only data from phantom-based feasibility studies are available, but these indicate that several of the typical incidences reported by IRP, IAEA, and data bases such as NRC could be detected by EMT. Therefore, clinical assessment of EMT is urgently needed as the next step, ideally well integrated to the current workflow.

A comparison to IVD and real-time imaging shows that none of these three techniques can address all of the most important error and variability items. Thus, a combination of multiple techniques will be needed. Promising combinations will depend on the clinical application, the likelihood of the errors in order to match the appro-

priate technique, and the level of certainty desired. Several of the potential errors can be caught by EMT during the check-cable run, i.e. before dose delivery. Treatment application should then be monitored by IVD, ideally in combination with EMT [13] or an in-room imaging modality, since IVD requires precise localization of the detector. In addition, IVD and EMT integrated into the workflow can act as a trigger for follow-up imaging examinations, e.g., in case of organ deformation exceeds to be defined thresholds. Challenging for all combinations is the registration of coordinate systems needed for fusion of EMT/IVD data with the (volumetric) image set used for treatment planning. For some clinical sites, fluoroscopy, C-arm based cone-beam CT, or ultrasound may be used as an imaging modality in the treatment room, providing sufficient image quality for establishing a relation between EMT/IVD coordinates and anatomy, but not necessarily sufficient for adaptive treatments.

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