Application of photogrammetry reconstruction for hyperthermia quality control measurements

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A R T I C L E   I N F O

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A B S T R A C T

Purpose: Hyperthermia is a cancer treatment in which the target region is heated to temperatures of 40–44 °C usually applying external electromagnetic field sources. The behavior of the hyperthermia applicators (antennas) in clinical practice should be periodically checked with phantom experiments to verify the applicator’s performance over time. The purpose of this study was to investigate the application of photogrammetry reconstructions of 3D applicator position in these quality control procedure measurements.

Methods: Photogrammetry reconstruction was applied at superficial hyperthermia scenario using the Lucite cone applicator (LCA) and phased-array heating in the head and neck region using the HYPERcollar3D. Wire-frame models of the entire measurement setups were created from multiple-view images and used for recreation of the setup inside 3D electromagnetic field simulation software. We evaluated applicator relation (Ra) between measured and simulated absolute specific absorption rate (SAR) for manually created and photogrammetry reconstructed simulation setups.

Results: We found a displacement of 7.9 mm for the LCA and 8.2 mm for the HYPERcollar3D setups when comparing manually created and photogrammetry reconstructed applicator models placements. Ra improved from 1.24 to 1.18 for the LCA and from 1.17 to 1.07 for the HYPERcollar3D when using photogrammetry reconstructed simulation setups.

Conclusion: Photogrammetry reconstruction technique holds promise to improve measurement setup reconstruction and agreement between measured and simulated absolute SAR.

Introduction

Hyperthermia is a cancer treatment in which the target region is heated to temperatures of 40–44 °C usually applying external electromagnetic (EM) field sources [1]. The clinical efficacy of combining hyperthermia treatment with standard radiotherapy and/or chemotherapy was demonstrated in several randomized trials for various locations [2,3,4,5]. Quality assurance of hyperthermia treatment systems is crucial for ensuring treatment quality, which is especially important in multicenter clinical trials [6,7,8]. Temperature information during hyperthermia is usually obtained from a limited number of temperature measurements points placed in invasive catheters [9]. Spatial 3D temperature profiles can be determined using hyperthermia treatment planning (HTP) [10]. HTP represents optimization of treatment parameters such as amplitude and phase of antennas feeding signals in order to maximize deposition of absorbed EM power and/or temperature inside the target region [11,12,13].

HTP is applied for clinical treatment guidance in phased-array systems in deep hyperthermia in the pelvic and the head and neck (H&N) regions [14,15,10,16,17]. Further it allows detailed analyses of hyperthermia treatments, comparison of different hyperthermia heating strategies and also possible creation of the guidelines for limiting personnel EM exposure during hyperthermia treatments [18,19,20]. In superficial hyperthermia where single antennas or incoherent arrays are used, application of HTP is confined to special situations where the target is close to critical organs, contains metallic structures, or for

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applicator selection [21,22,23,24]. Patient specific HTP is routinely applied since 2011 for all deep hyperthermia applicators at the Erasmus MC, i.e. HYPERcollar3D, Sigma 60 and Sigma Eye [25,26]. HTP is also a great tool that can provide extrapolation of the 1D knowledge from temperature probes to 3D profiles [11]. Such 3D predictions require a validated translation between simulated and measured characteristics of the hyperthermia system.

Quality control is achieved by phantom heating measurements in which applicators such as the Lucite cone applicator (LCA) are positioned on a tissue mimicking phantoms [7]. Such a measurements could provide insight in the quantitative performance of the applicators over time and quantitative treatment quality control in multi-center studies. For comparison of simulated and measured EM characteristics, correct translation of the measurement setup in EM simulation software is crucial. A photogrammetry reconstruction from multiple view images can provide accurate and efficient solution for reconstruction of the measurement setups. Earlier we demonstrated that an accuracy of ±1.02 mm is feasible using the photogrammetry reconstruction method on a clinical superficial hyperthermia setup of six LCAs [27].

The purpose of this study was to investigate the application of photogrammetry technique for accurate reconstruction of hyperthermia phantom measurement setups. We used our superficial LCA and head and neck HYPERcollar3D hyperthermia applicators for quality control measurements. We reconstructed the LCA position in correspondence to the phantom surface under the LCA aperture and for the HYPERcollar3D we reconstructed the position of an anthropomorphic phantom inside the applicator. For both setups, we compared spatial displacement of manually created and photogrammetry reconstructed setups. Relation between absolute measured and predicted specific absorption rate (SAR) were calculated for all measuring points in the experimental setups, providing quantitative information for both applicators.

**Methods**

For clinical HTP, it is important to apply validated models of the real HT systems. Hence, the model implementation must be verified by quality assurance measurements using phantoms, in which an accurate representation of the measurement setup is a key factor to minimize the differences between predictions and measurements. Hereto, we studied if photogrammetry reconstruction for superficial and deep head and neck measurement setups allow to improve the agreement between predicted and measured SAR distributions.

**Measurement setups**

The application of the photogrammetry reconstruction for accurate phantom reconstruction was tested for superficial and deep H&N hyperthermia applicator setups. For both experiments, we prepared muscle equivalent phantoms for 434 MHz following the recipe of Ito et al. and verified its dielectric properties using dielectric assessment kit (DAK-4, Speag, Zürich, Switzerland) [28].

**Superficial hyperthermia**

Fig. 1 shows a schematic measurement setup for a single LCA with the actual setup displayed in Fig. 2a. A generator with a maximum power of 250 W (ALBA Hyperthermia System, Rome, Italy) at 434 MHz was connected through a circulator (M/A-COM, Lowell, Massachusetts, USA) and bidirectional coupler (3020A, Narda, Hauppauge, NY, USA) to the panel C-type connector of the LCA. The circulator was connected to a 50 Ω load protecting the generator against high amount of reflected power. Forward and reflected power was measured using a digital power meter (EMP-442A, Agilent, Santa Clara, California, USA) with additional 20 dB attenuators (R412720000, Radial, Rosny-Sous-Bois, France). The characteristics of the bidirectional coupler were measured at the beginning of each experiment with a vector analyzer (5751A, Agilent, Santa Clara, California, USA). The LCA was positioned at the top of 20 mm thick water bolus placed at the top of 10 mm and 80 mm thick phantom layers mimicking muscle tissue at 434 MHz. The center of the applicator was manually aligned with the phantom center lines at the 10 mm deep surface, such that the LCA aperture would be projected in 10 mm depth as shown in Fig. 2c. During this procedure, we marked this center line by a pen at the phantom and then we positioned a 10 mm thick phantom layer, at which we drew this center line as well, aiming to overlap these two lines. Afterwards, following this center line, we positioned the water bolus on top of the phantom. The LCA was secured on top by a fixation arm [27]. For the heating experiments we used four multi sensor fiber optic temperature probes (FISO FOT-NS-577E, Fiso, Quebec, Canada), with in total 14 temperature sensors, input power of 160 W and a heating period of 180 s, resulting in a maximum temperature increase of 2.3 °C per minute, i.e. in accordance with the ESHO quality assurance guidelines [7]. Details of the four temperature probes placements at 10 mm depth measurement plane of the muscle equivalent phantom are shown in Fig. 2c.

**Head and neck hyperthermia**

For the HYPERcollar3D measurements, we used the clinical measurement setup with integrated measurement of the forwarded amplitude and phase together with the reflected power [29]. The 434 MHz signal is generated using a direct digital synchronizer allowing independent adaptation of amplitude and phase of each of the 12 channels. These 12 signals are individually driven into identical amplifiers as also used for the superficial heating experiments (Fig. 1). For each channel forward and reflected power together with forward phase is registered. Fig. 2b shows the HYPERcollar3D experimental setup together with H&N anthropomorphic muscle equivalent phantom. The phantom was positioned inside the HYPERcollar3D following our clinical routine in order to replicate the position in the HTP process. In this procedure, the relative position of the tip of the nose with respect to a fixed control point at the applicator is measured in cranial-caudal and dorsal-ventral directions. In addition, the rotation of the head phantom in the sagittal

![Fig. 1. Schematic of measurement setup for the Lucite cone applicator (LCA).](image-url)
plane was measured and the nose tip was centered in left–right direction using the laser alignment system [30]. For the heating experiments, we used equal amplitude and phase settings to all channels, 17 temperature measurement points sensors placed in six catheters (FISO FOT-NS-577E, Fiso, Quebec, Canada) and a 90 s heating interval at a total power of 300 W, which resulted in maximum temperature increase of 6.2 °C per minute.

**Photogrammetry reconstruction**

Photogrammetry scene reconstruction involves determining the 3D geometry properties of the real objects from a set of images taken from different view angles [31]. Both setups were reconstructed using images with resolution of 2560x1920 pixels from a standard SONY (Minato, Tokyo, Japan) DSC F707 CyberShot camera in the commercial PhotoModeler Scanner software (v.2012, Eos System Inc., Vancouver, Canada). For all reconstructions we took a series of photos around the setups at a 360° angle aiming to maximize the overlap between two adjacent photographs. The camera was set to manual focal distance of 500 mm, to ensure all photos were taken with the same settings, for which a standard calibration inside the PhotoModeler software was done prior the experiment. For the superficial setup, we took 39 images since we reconstructed the whole setup in three steps, i.e. 1) the LCA position, 2) the phantom surface position and 3) the location of the fiber-optic catheters placed under 10 mm thick top phantom layer (see Fig. 2a Fig. 2c). After taking the initial set of 18 images around the setup for the LCA position reconstruction (step 1), we removed the LCA and the water bolus and took another set of six images for the phantom surface reconstruction (step 2). Next, we removed the 10 mm phantom layer and took a final set of 15 images for catheter reconstruction, with their placement shown in Fig. 2c. Connection among all three image sets in PhotoModeler was implemented via common points which were present at all three image sets. For the HYPERcollar3D setup, 29 images were taken with the targets placed on the applicator and the phantom surface as shown in Fig. 2b. Fig. 2d shows the position of six thermometry catheters inside the anthropomorphic H&N phantom model created from segmentation of 201 CT slices. For this setup the thermometry measurements points were reconstructed from the CT.

**Simulation setups**

We compared absolute measured SAR from fiber-optic sensors with simulated SAR distributions from manually created and photogrammetry reconstructed setups for both applicators. In SEMCAD X, the LCA model was placed on the top of a 180 × 180 × 20 mm³ water bolus model and a 400 × 300 × 90 mm³ phantom model for the manual superficial hyperthermia setup. The center of the LCA aperture was positioned exactly above the center line of the real phantom used during the measurements, as shown in the Fig. 2c. The predicted SAR values at the temperature sensors locations were obtained using 3D interpolation of the predicted EM field. For the HYPERcollar3D we followed the clinical HTP procedure. The assignment of the nose control point at the H&N anthropomorphic phantom (see Fig. 2d) was done by a physicist experienced in clinical HTP process. Photogrammetry setups were created from the reconstructed models from multiple view images, which were imported into SEMCAD X and overlapped with the corresponding 3D applicator models. For the superficial LCA setup, we also modified the flat phantom surface according to the reconstructed points, taking into account

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**Fig. 2.** a) superficial hyperthermia measurement setup with the Lucite cone applicator (LCA) and layered flat muscle equivalent phantom, b) HYPERcollar3D head and neck hyperthermia setup with anthropomorphic phantom, c) detail of catheter placement for superficial setup, d) SEMCAD X 3D model created from CT images with highlighted six catheter temperature probes.
account small surface irregularities. Additionally, measurement positions of the fiber optic temperature sensors were also reconstructed. For the photogrammetric H&N simulation setup we reconstructed position of the anthropomorphic phantom inside the HYPERcollar3D model.

Incident power \( P_{\text{inc}} \) (W), i.e. power entering into the calculating domain, was normalized to 1 W for the LCA and to 1/12 W for each antenna of the HYPERcollar3D to allow comparison of measured and simulated SAR. Hence, we corrected for the reflections caused by an imperfect impedance matching. \( P_{\text{inc}} \) can then be expressed as:

\[
P_{\text{inc}} = P - P_{\text{ref}} = P \left( 1 - |S_{11}|^2 \right)
\]

where \( P \) (W) is input power of the applicator, \( P_{\text{ref}} \) (W) is a reflected power and \( |S_{11}| \) (–) is the input voltage reflection coefficient.

All metallic parts in the simulations were modeled as perfect electric conductor (PEC) material. The dielectric properties for both simulation setups at 434 MHz are summarized in Table 1. For the superficial LCA setup, we used a gradient grid varying from 0.25 mm for the feeding parts, via 1 mm inside the applicator including up to 40 mm depth in the flat phantom to 2.5 mm outside this volume (34 MCells in total). We used a 30 period harmonic 434 MHz signal and calculation at two GTX 1080 cards took 37 min. For the HYPERcollar3D simulations, we used a uniform 1.25 mm finite difference time domain (FDTD) grid, resulting in 81 MCells, and 15 periods of harmonic 434 MHz signal. The harmonic simulation per antenna at two GTX 1080 cards took ten minutes. Afterwards, we normalized for incident power and combined the electric fields using identical amplitude and phase settings aiming on creating a central focus, which resulted in one combined SAR distribution with a central focus in the anthropomorphic phantom.

Comparison of predicted and measured SAR

The temperature simulation can be calculated using the Pennes bioheat [32] equation.

\[
\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) - \rho c_s \psi_{\text{paw}}(T - T_b) + \rho \text{SAR} + \rho Q
\]

where \( \rho \) (J/kg-K) represents the specific heat capacity, \( \rho \) (kg/m³) the density, \( k \) (W/m-K) the thermal conductivity, \( c_s \) (J/kg-K) the specific heat capacity of blood, \( \psi_{\text{paw}} \) (W/kg) the blood perfusion rate, \( \text{SAR} \) (W/kg) specific absorption rate, \( Q \) (W/kg) the metabolic heat generation, \( T_b \) (K) the temperature of the blood. Since for both experiments we used short heating time, i.e. 180 s for the LCA and 90 s for the HYPERcollar3D, the conductive and in equation (2) can be neglected. The equation (2) can be further simplified due to the no perfusion and metabolic heat generation in phantom to:

\[
\text{SAR} = \rho \frac{\Delta T}{\Delta t}
\]

where the specific heat capacity of the phantom \( c = 3640 \) J/kg-K, \( \Delta T \) (K) is the temperature increase, \( \Delta t \) (s) is the heating time.

Predicted and measured SAR values were compared for all points in which the temperature elevation was measured. For both experiments, measured SAR was calculated for each probe following equation (3) and, after normalization to an incident power of 1 W, compared to the predicted SAR values. After linear curve fitting of measured and simulated SAR comparisons from individual temperature sensors and their corresponding positions in simulations, we calculated for each applicator and both manual and photogrammetry reconstructed setups the applicator relation \( R_a \) (–) describing the dependence between measured and simulated SAR, expressed as:

\[
R_a = \frac{\Delta \text{SAR}_{\text{meas}}}{\Delta \text{SAR}_{\text{sim}}}
\]

where \( \Delta \text{SAR}_{\text{meas}} \) (W/kg) and \( \Delta \text{SAR}_{\text{sim}} \) (W/kg) are the increments in measured and simulated SAR from the linear fitted data. This technique was applied rather than establishing \( R_a \) from mean or median rates of the measured and simulated SAR from individual sensors, to avoid averaging SAR differences between probes with lower and higher rates. \( R_a \) factor calculated from individual comparisons, in scenario where half of the probes obtained lower and half higher measured SAR than simulated, could result in perfect agreement, i.e. \( R_a = 1 \).

Results

Measurement setups

Measurements of the reflection coefficient \( |S_{11}| \) for the LCA obtained by tuning pin adjustment to minimize \( |S_{11}| \) at 434 MHz and for the 12 channels of the HYPERcollar3D are shown in Fig. 3. The value of \( |S_{11}| \) for the LCA and HYPERcollar3D at 434 MHz were \(-16.9\) dB and \(-11.3 \pm 1.4\) dB (mean ± standard deviation).

Photogrammetry reconstruction and simulation setups

Fig. 4a) and Fig. 4b) show 3D the reconstructed “wire-frame” LCA and HYPERcollar3D experimental setups from multiple-view images using PhotoModeler software including the position from which the photos were taken from around the experimental setup. Subsequently, we overlapped the LCA model over the “wire-frame” PhotoModeler model, reconstructed the temperature measurement catheter position and surface of the phantom, resulting in the simulation setup as shown in Fig. 4c). The surface of the phantom was created using Delaunay triangulation from the photogrammetrically reconstructed points at the phantom surface. This enabled to capture surface irregularities down to 2.3 mm in the direction of Y axis (see Fig. 4c) during the measurements, and to translate them into the 3D model used by SEMCAD-X for the SAR predictions. For the H&N setup, the “wire-frame” model was first overlapped over the HYPERcollar3D model and second over the anthropomorphic phantom model for the “wire-frame” model. With this procedure, we obtained accurate position of the anthropomorphic phantom inside the HYPERcollar3D model, as shown in Fig. 4d). The photogrammetry reconstruction in PhotoModeler of each setup took us around five hours followed by 15 min necessary for creating the simulation setups in SEMCAD X.

Comparing manual and photogrammetry reconstructed positions of the LCA and of the HYPERcollar3D, we found a displacement of 7.9 mm with vector (-6.4, -2.3, -4.1) for the center of the LCA aperture and 8.2 mm (0.6, -8.1, 1.4) for the center of the HYPERcollar3D. For the superficial setup, we also detected LCA rotations of (0.5, -0.3, 0.6) degrees with respect to X, Y, and Z axis when comparing setups in which LCA was manually positioned and in which LCA position was determined using photogrammetry technique. We imported the photogrammetry reconstructed simulation setup into the manually created setup in SEMCAD X and manually adjusted its position in order to overlap the positions of individual fiber optic sensors and the phantom. From this procedure, we obtained the translation and rotation of one simulation setup with respect to the second one. For the H&N setup we applied the same procedure by overlapping the position of the anthropomorphic

### Table 1

| object name              | \( \sigma \) (S/m) | \( \varepsilon_r \) | \( \rho \) (kg/m³) |
|--------------------------|-------------------|--------------------|------------------|
| Deionized water          | 0.043             | (-)                | 1000             |
| Phantom (muscle equivalent) | 0.800          | 56.0               | 1080             |
| Plexiglas                | 0.004             | 2.2                | 1180             |
| Teflon                   | 0.003             | 2.1                | 2200             |
phantom for both simulation setups.

**Comparison of predicted and measured SAR**

Fig. 5a) and Fig. 5b) show a point-wise comparison of the measured and simulated SAR normalized to 1 W incident power for locations of the fiber-optic temperature measurement probes for the LCA and the HYPERcollar3D, respectively. The $R_a$ relation, calculated form linearly fitted data represented by solid lines in Fig. 5a and Fig. 5b ($R_a = 1$ represents perfect match between measured and simulated SAR). For the manually created LCA setup the $R_a = 1.24$ compared to 1.18 for the photogrammetry reconstructed setup. The example how the $\Delta SAR_{\text{meas.}}(W/kg)$ and $\Delta SAR_{\text{sim.}}(W/kg)$ were established from fitted data is shown for the photogrammetry reconstructed setup in Fig. 5a). In this

Fig. 3. Measured reflection coefficient ($|S_{11}|$) for a) the LCA as function of frequency, b) for the 12 channels of the HYPERcollar3D at 434 MHz.

Fig. 4. Photogrammetric reconstruction in PhotoModeler software including camera positions from where photos were acquired (blue-red-green blocks) of a) superficial LCA, b) H&N HYPERcollar3D setups and their corresponding SEMCAD X simulation setups c) LCA and d) HYPERcollar3D. Note the “triangulated” reconstructed phantom surface for the LCA setup which represents surface spatial irregularities. Yellow surfaces in figure d) used for overlapping the reconstructed scene and the HYPERcollar3D and the H&N phantom models.
case, increments of the 3D phantom model for a) LCA (14 comparisons) and b) HYPERcollar3D - HC3D (17 comparisons). Applicators relations

Fig. 5. Comparison of measured and simulated SAR normalized to 1 W input power from temperature measurement sensors and their corresponding location inside the 3D phantom model for a) LCA (14 comparisons) and b) HYPERcollar3D - HC3D (17 comparisons). Applicators relations $R_a$ (dependency between measured and simulated SAR) for linearly fitted data when comparing manual and photogrammetry setups were improved (better agreement) from 1.24 to 1.18 for LCA and from 1.17 to 1.07 for the HYPERcollar3D. In figure a) is shown how the $R_a = 1.18$ for the photogrammetric reconstruction of the LCA was obtained from $\Delta \text{SAR}_{\text{meas}} = 0.834 \text{ W/kg}$ and $\Delta \text{SAR}_{\text{sim}} = 0.706 \text{ W/kg}$.

Discussion

Photogrammetry reconstruction from multiple-view images holds promise for reconstruction of the measurement setups in hyperthermia quality control experiments. For the superficial setup, we have successfully reconstructed the position of the LCA according to the position of the fiber-optic probes placed in 10 mm depth of the muscle equivalent phantom. Additionally, we were able to detect the 2.3 mm irregularities by using the photogrammetric reconstruction of the phantom surface under the LCA aperture. This “non-flat” effect caused by extra weight of the water bolus and fixed LCA can be even more prominent for larger phantoms and applicators without fixation capabilities in predefined treatment position as it is possible for the LCA. For the HYPERcollar3D, the anthropomorphic phantom positioning was reconstructed from multiple view images while the positions of the probes inside were determined using CT images. The LCA rotation of (0.5, -0.3, 0.6) degrees and a spatial displacement of 7.9 mm (LCA) and 8.2 mm (HYPERcollar3D) resulted in predicted SAR difference of 5.1 % (LCA) and 9.3 % (HYPERcollar3D), when using photogrammetry reconstruction compared to manually created setups. We obtained a better match between measured and predicted SAR for both applicators when using the photogrammetry reconstructed setups.

At this moment, the manual photogrammetric position reconstruction process takes up to five hours, which could be a limiting factor for routine application in hyperthermia quality control measurements and comparisons of predictive and measured applicator heating characteristics. This time is also more than the time needed in earlier work in which one and half hour was required to reconstruct six LCAs setup from ten photos [27]. This increase in reconstruction time in this study for superficial LCA setup was caused by applying of 39 photos, since we aimed at maximum accuracy. However when taking into account the amount of photos and the reconstruction time used in both studies (one and half hour reconstructing from ten photos vs five hours reconstruction from 39 photos) we obtained faster reconstruction in this study. Since we applied more photos than in the previous study, and additionally applied coded targets, we expect the reconstruction accuracy to be better than ± 1 mm. Accuracy might also be improved by use of a newer camera with a higher resolution. For the photogrammetric reconstruction we used dedicated commercial photogrammetric software, however there are several freely available photogrammetric programs, which should be also applicable for these purposes [33,34].

During the reconstruction procedure, we used a combination of a high amount of dotted targets and coded-targets, which are automatically recognized and connected among multiple images by the PhotoModeler software. Especially for the HYPERcollar3D setup, the dotted targets enabled an easier visual check of the manual overlapping procedure in SEMCAD X for curved surface reconstructions. The possibility to overcome time consuming reconstruction is to use only automated coded targets placed at predefined positions on the applicator and anthropomorphic phantom. These positions can be transferred to the HYPERcollar3D SEMCAD X model by manual measurements and for the phantom by placing copper marks at those locations during the CT scan. Since every coded target in PhotoModeler has its unique identification number, we would be able to automatically position the phantom inside the applicator. For the superficial LCA setup implementation a similar procedure is feasible, however the position of the thermometry catheters will still need to be reconstructed manually. In clinical practice the invasive catheter track can be reconstructed from the CT scan which can also be used for applicator position by placing a “dummy” applicator in treatment position at the CT scan. Kok at el. demonstrated that this technique enables a complete superficial hyperthermia treatment planning procedure [35].

The LCA positioning fixation system allowing in clinical practice arbitrary LCA position was used in this study to secure LCA at the top of the phantom and the water bolus. This resulted along with the spatial displacement also in the LCA rotation of (0.5, -0.3, 0.6) degrees with respect to X, Y, and Z axis. Even though we were able to detect this LCA rotation by using the photogrammetry reconstruction, this effect could be minimized by applying recently introduced solid hydrogel water bolus, which could make the LCA positioning easier [36]. Another possibility is to connect the applicator itself and the phantom with rigid structure created by e.g. 3D printing technique, such as recently used for an antenna verification measurements of newly developed MRcollar applicator [37]. However this technique in which applicator and phantom are embedded in single object is suitable only for the applicators in the development. For quality assurance of pre-clinical and clinical systems it is feasible to create accurate 3D water bolus based on CT or MRI images [38].

The photogrammetry reconstruction procedure is a part of our efforts
towards converting qualitative into a quantitative validation of our superficial and deep H\&N clinical hyperthermia applicators. Earlier, we showed that absolute SAR is crucial since identical temperature coverage of the superficial horn applicator can be achieved by tuning of the applicator input power for different perfusion models in a superficial layered setup [39]. This advocates that blood perfusion and input power are related and when trying to achieve absolute temperature predictions real applicator efficiency is required. For absolute SAR predictions it is further important to use as complete 3D model of the hyperthermia applicators as possible. In contrast to this study, we previously found for seven clinically used LCAs, higher predicted absorbed power in muscle equivalent phantom than measured absorbed power using 3D robotic scanning EM system (R̃p ranged from 0.75 to 0.92) [40]. In that study, incomplete model of the LCA without the tuning pin was used resulting in higher predicted power absorption in the phantom model in comparison to complete LCA model as shown in Fig. 4c.

Quantitative 3-dimensional SAR or temperature predictions by HTP are pivotal for the process of discovering relationship between clinical outcome and applied thermal dose. An alternative to convert “qualitative predictions” into quantitative thermal dose parameters is 3D temperature monitoring during hyperthermia treatments. Currently, the only technology for 3D temperature is magnetic resonance thermometry [41]. These systems provide a unique opportunity for validation of the hyperthermia systems in-vivo in 3D [42]. Combining quantitative thermal modelling with magnetic resonance thermometry has a potential providing 3D accurate thermal dosimetry in the entire treatment process: pre-treatment decision making and optimization, treatment execution and treatment evaluation [43]. Quantitative thermal modeling will be also an indispensable tool for the development and clinical implementation of novel devices and techniques leading to improved hyperthermia administration and patient care.

The superficial hyperthermia quality assurance guidelines recommend verifying the applicators performance at the 10 mm plane and also in 2D depth profiles (XY and YZ planes in Fig. 4c) through the aperture center using the infrared camera [7]. These cross-sections need to be measured in consecutive experiments where the applicator is removed and placed back for the next measurement. This can lead to slightly different applicator positions which will not influence the outcome of the quality assurance measurements focused on assessing the heating capabilities of the applicator for the clinical application of superficial heating. However, when phantom experiments are used for comparison with predicted values, an accurate translation of the measurement setup into the simulation software is necessary. As shown in our case, an error of 5.1 % in measured SAR was found when using only manual applicator placement for creation of the superficial 3D simulation setup.

Conclusion
Translation of two hyperthermia measurement setups into 3D EM field simulator software was achieved using photogrammetric reconstruction. The best agreement between measured and predicted SAR was obtained for both LCA and HYPERcollar3D applicator when the applicator and phantom set-up was reconstructed using the photogrammetry technology. The difference between predicted and measured SAR was reduced by 5.1 % and 9.3 % using photogrammetry compared to manual reconstruction for the LCA and the HYPERcollar3D, respectively. Photogrammetry reconstruction technique has a potential to improve measurement setup reconstruction and agreement between measured and simulated absolute SAR. Ultimately, the latter will become mandatory to move forward to quantitative hyperthermia treatment planning of the applied SAR distribution.

Declaration of Competing Interest
G. C. van Rhoon and M. M. Paulides have financial interest in Sensius BV. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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