Localization of an HDR brachytherapy source using MR artifact simulation and phase-only cross correlation

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Purpose In high-dose-rate (HDR) prostate brachytherapy, needles and a high-intensity source of radiation are inserted into a tumor temporarily, to deliver a boost for focal primary or salvage treatment. Image guidance is of great importance (e.g. during needle positioning) for quality assurance and safety. MRI is the preferred imaging modality because of its excellent high soft tissue contrast. At our institution, a robotic MR-guided HDR brachytherapy procedure is being developed [1] and one of the aims is real-time tracking of the HDR source to accurately determine the positions where the dose is delivered. The materials used are primarily paramagnetic and/or conductive (e.g. titanium needles, an iridium source (Ir-192) in a steel capsule and a steel cable connecting the source to the afterloader), introducing several challenges. Firstly, the magnetic susceptibilities of these materials generate image artifacts through induced perturbations of the static B_0 field. Secondly, the steel cable may heat and experience forces due to RF pulses and gradient switching. The purpose was to investigate if an HDR source can be localized, and to what extent this depends on the materials used. This was done using gradient echo imaging in combination with artifact simulation and template matching. Simulations and experiments were performed with two types of needles (titanium and plastic) and two types of cables (steel and plastic) connected to the source.

Methods *Experimental set-up*: Measurements were done with a titanium and a plastic needle inserted into an agar phantom. Two dummy sources were constructed: one consisting of a solid steel capsule (radius: 0.45 mm, length: ~4.5 mm) welded to the distal end of a steel cable (radius: 0.45 mm) and one similarly sized steel capsule fixed in the tip of a plastic catheter. The dummy sources were brought into the needles, in the tip and at ~2 cm from the tip respectively. Measurements were done with the needles parallel to B_0 and under an angle (~20º). *Imaging parameters*: MR imaging was performed on a 1.5T MR scanner (Achieva, Philips Healthcare), using a 2D gradient echo sequence (TR/TE 9.3/3.5 ms, slice thickness 10 mm, FOV 160x160 mm, acq. matrix 160x160, flip angle 30º). *Simulations:* The geometries of the two sources and the steel cable were modeled as solid steel cylinders, on a cubic grid with voxel size 0.25^3 mm^3. The plastic cable was neglected. Since the susceptibilities of the objects were not exactly known, the susceptibility differences $\Delta\chi$ (between object and phantom) were chosen such that the simulated artifacts matched to the experimental artifacts. Forward calculations of the susceptibility induced field shifts were performed using a Fourier-based convolution method in combination with virtual zero-padding [2], at a voxel size of 0.25^3 mm^3. The influence of spatial encoding was neglected and the susceptibility induced field shifts were converted to the simulated complex MR signal. These signals were resampled to a grid with a larger voxel size of 1x1x10 mm (equal to experimental voxel size) by complex averaging, simultaneously taking dephasing into account. *Post-processing*: Phase-only cross correlation (POCC) was performed to determine the translation factor between the complex data of the experimental image $I_1(x,y)$ and the simulated image $I_2(x,y)$ containing the simulated object at its center [3]. The POCC is a normalized convolution, calculated as a multiplication in *k*-space: $POCC(x,y) = \mathrm{FFT}^{-1}\left[\left(I_1(k_x,k_y)\cdot I_2^*(k_x,k_y)\right)/\left(\left|I_1(k_x,k_y)\cdot I_2^*(k_x,k_y)\right|\right)\right]$. The location of the source in the experimental image followed from the coordinates of the maximum in the POCC image.

Results and discussion The $\Delta\chi$'s that were found to match the simulations to the experiments were: steel capsule connected to plastic cable: $\Delta\chi$=15.000 ppm; steel capsule connected to steel cable: $\Delta\chi$=6.700 ppm; and steel cable: $\Delta\chi$=7.200 ppm. The simulations strongly resembled the experimental data for both cases (with the source aligned with B_0 and under an angle) as shown in Fig. 1a and 1c respectively. POCC resulted in a high correlation at a single position (see Fig. 1b), providing the exact location of the source, irrespective of the presence of field distortions of the second dummy source and irrespective of the placement of the source in the needle (in tip or at ~2 cm from tip). However, validation of the position accuracy needs to be performed in the near future. The influence of the needles was small compared to the artifacts of the sources, rendering both the titanium and plastic needle suitable. Although localization of the sources was possible with both types of cables, the steel cable was less suitable for simulation, since the welding between the capsule and the cable makes accurate simulation of the artifact difficult. Moreover, when positioned at an angle with B_0, the steel cable induced large artifacts around the cable, hindering the ability to image surrounding tissue. Another important aspect is that the steel cable introduces safety concerns (risk of heating and torques). Altogether, these facts give preference to the use of a plastic drive wire.

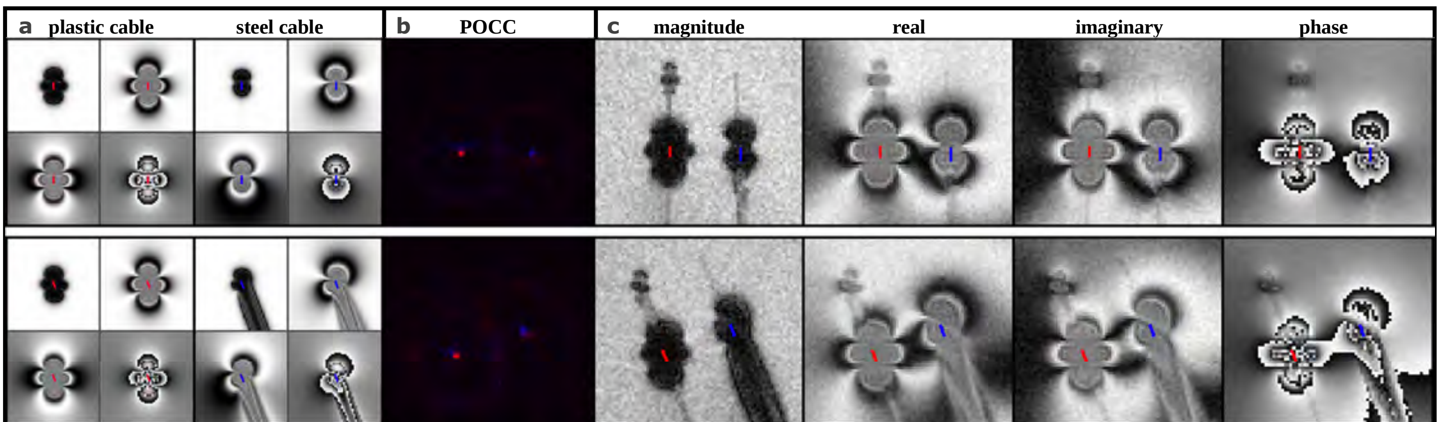

Fig 1. *Example of a situation with the source with plastic cable in the titanium needle (left, indicated in red) and the source with steel cable in the plastic needle (right, indicated in blue), placed aligned with B_0 (top row) and under an angle (bottom row).* ***a)*** *Simulated artifacts around the sources (magnitude, real, imaginary and phase images).* ***b)*** *The POCC's from both sources shown on top of each other (red: source with plastic cable; blue: source with steel cable).* ***c)*** *Experimental artifacts, with the positions of the sources that followed from POCC overlaid in red (plastic cable) and blue (steel cable) on the images.*

Conclusion Accurate determination of the position of an HDR source can be done retrospectively, by simulating its artifact in a gradient echo image and matching the simulated artifact to the experimental data by means of POCC. Besides, it can be concluded that it would be favorable to develop a plastic drive wire (suitable for use in an afterloader) that connects the source to the afterloader, in order to make the HDR brachytherapy treatment more appropriate for use inside the MR scanner.

References 1)Van den Bosch M.R. et al., Phys. Med. Biol. 2010; 55:N133-40. 2)Bouwman J.G. et al., MRM 2012; 68:621-30. 3)De Oliveira et al., MRM 2008; 59:1043-50.