Optimizing Accuracy and Precision of Micro-coil Localization in Active MR Tracking under low SNR conditions

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Introduction: Real-time active tracking of interventional devices using magnetic resonance (MR) has been proposed as an alternative to x-ray visualization during interventional procedures (1-3). Active device visualization employs micro-coils that detect MR signals in the presence of applied magnetic field gradients which cause the frequency of the MR signal to be proportional to its position. Since the sensitivity of a micro-coil is spatially limited, Fourier transformation of the signals provides a peak in the power spectrum which is ideally located at the center of the micro-coil. When the Signal-to-Noise Ratio (SNR) of the detected MR signals is high, the accuracy and precision of tracking are well suited to a wide variety of applications. However, non-idealities of the MR tracking environment can restrict MR tracking rate and robustness. Severe challenges to robust and fast MR tracking can occur when MR signals detected by the tracking coil arise only from regions outside of the coil (e.g. in a lumen-less catheter or biopsy needle). This results in less efficient detection, poorer accuracy, and a complicated phase sensitivity profile.

Several methods to improve tracking accuracy in low SNR conditions have been proposed. Hadamard Multiplexing reduces resonance offset errors by simultaneously encoding position with unique combinations of three orthogonal localizing gradient pulses in each of four tracking excitations. The detected MR peak locations are input into four linear equations to determine the X, Y and Z addresses of the coil and an error term that corresponds to the resonance offset (2). Phase Field Dithering is another method to increase the robustness of active MR tracking in low SNR conditions. This method employs dephasing magnetic field gradient pulses that are applied orthogonal to the frequency encoding gradient. Tracking is repeated over a cycle length of N in which the dephasing gradients are rotated about the frequency encoding direction. The application of the orthogonal dephasing gradient has two effects on the detected MR signal. First, it serves to dephase signals over large regions, which in turn reduces the size of the MR signals that are coupled into the tracking coil. Second, it changes the distribution of MR signal phase in the region around the MR tracking coil. The orthogonal dephasing gradient can either improve or hurt the MR tracking signal in an unpredictable fashion. Consequently, MR tracking data acquired over the entire cycle length is combined to extract out the best tracking information (4).

We have developed an additional strategy to increase the robustness of active MR tracking in these low SNR conditions. This new method improves upon the conventional "max pixel" approach to MR tracking peak detection in the power spectrum by recognizing that the expected profile of the MR tracking peak varies with orientation, lumen content and local magnetic susceptibility. For example, a fully immersed symmetric micro coil aligned transversely in B0 will have maximum signal intensity at both ends of the coil, and small fluctuations in the signal due to noise will cause the detected coil location to hop between two maxima. We propose using a new method using a centroid algorithm to more accurately determine the position of the micro coil. The accuracy of tracking using all three methods was modeled using electromagnetic simulations. The accuracy and precision of the approach was then verified experimentally.

Materials and Methods: Figure 1 shows a graphical representation of the centroid method. The method finds the primary and secondary maxima, then calculates the centroid (or center of the "signal intensity") using a fixed window set to 2.5 times the coil size. The algorithm robustly determines the center of the coil for both bifurcated and monotonic MR tracking peaks.

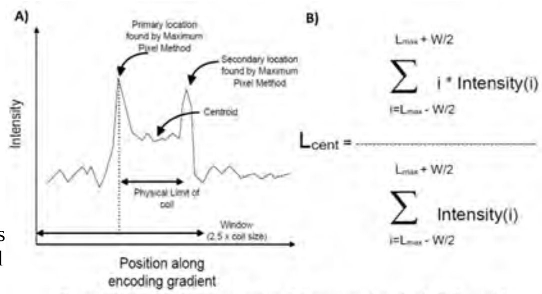

Figure 1 A) graphical representation of the centroid method. B) Centroid peak detection calculations

The magnetic field profile of a solenoid coil model scaled to the size of a typical tracking coil (2 mm diameter, 4 mm in length, and 10 windings) was modeled with electromagnetic simulation software (Ansys HFSS). The B1 sensitivity vector profiles were simulated via the Finite Element method and exported to Mathworks Matlab for further data processing. In order to investigate the effects of the coils orientation with respect to the main magnetic field, the B1 sensitivity vector profile was rotated in 5 degree increments around the X and Z axis producing B1 sensitivity vector profiles for 5,267 orientations of the coil. A simulated 90 degree excitation of the nuclear spins was performed for each orientation and the magnitude of the simulated signal was calculated by integrating along each axis (X, Y, and Z) to simulate MR tracking. We then applied the centroid and conventional "max pixel" peak detection algorithms to the simulated peaks to calculate the position of the micro coil at each orientation. Error was determined by calculating the distance from this calculated position to the true position of the micro coil in the simulation.

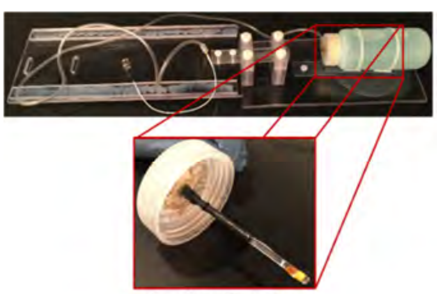

Figure 2 Experimental setup

A test coil was built by winding the inner conductor of a micro coaxial cable 15 times around a 3.5 mm solid plastic rod creating a lumen-less micro coil which was 3.5 mm in length. The end of the inner conductor was then soldered to the shield of the micro coaxial cable and the windings were glued in place. The plastic rod was mounted in the lid of a 500 ml cylindrical plastic bottle such that the micro coil was positioned in the center of the bottle. The micro coaxial cable was soldered to a micro mini MCX connector for attachment to the MR system. A test rig shown in Figure 2 was then built which allowed the bottle to be rotated 360 degrees in any plane in the magnet bore while keeping the micro coil at the isocenter of the magnet. Experiments were performed in a GE 430S MR scanner using tracking software developed earlier (3). The software allowed for the simultaneous use of Hadamard Multiplexing, Phase Field Dithering, and the Centroid algorithm for MR tracking.

The platform holding the bottle was placed in the magnet bore and the bottle rotated about the Y axis of the magnet. MR Tracking measurements were made every 10 degrees of rotation. At each position, the micro coil was first used as a TR coil (transmit and receive) to make an image from the micro coil to determine its "true" physical position. Tracking measurements were then recorded for 1 minute with the simultaneous use of Hadamard Multiplexing, Phase Field Dithering, and the Centroid algorithm. This provided 225 MR tracking samples at each orientation. The platform was then rotated to a vertical position and the phantom was rotated about the magnet's X axis with measurements taken every 10 degrees.

Results and Discussion: Figure 3 shows MR tracking peaks in the power spectrum generated at one orientation of the micro coil with electromagnetic simulation. Simulation showed a substantial improvement in MR tracking accuracy with the centroid method. The conventional "max pixel" algorithm had a mean error of 1.1531 mm with a worst case condition of 2.8438 mm. The centroid method on the other hand had a mean error of 0.0500 mm and a worst case condition of 0.1607 mm. This is a 1.1031 mm improvement in average tracking accuracy, and a 2.6831 mm improvement in the worst case condition.

The combined benefit of the centroid algorithm, Hadamard Multiplexing, and Phase Field Dithering provided remarkable MR tracking accuracy and precision experimentally. The mean positional error was only 1.7611 mm with a worst case condition of 4.7013 mm. The mean precision of MR tracking samples was 1.8917 mm. It is important to note that with the strategies employed here the positional error of the micro coil was less than the actual size of the micro coil (3.5 mm), even though there was no signal source inside the coil itself.

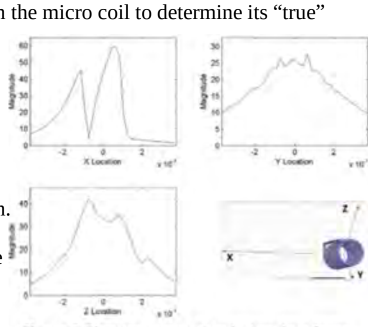

Figure 3 Electromagnet simulation data from one orientation of the tracking coil.

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