Camera placement for optical prospective motion correction: mechanical tolerance analysis

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Introduction and purpose: Optical prospective motion correction can prevent motion artifacts in neuroimaging [1]. A challenge with optical systems is that the camera is positioned and oriented relative to the imaging gradients, and the cross-calibration matrix representing the pose of the camera in the coordinate frame of the scanner may contain errors. Previous embodiments of optical motion tracking have placed the camera on the inside of the scanner bore [1,3,4] or mounted on the head coil [2]. We have observed that even with suboptimal cross-calibration, due to minor errors in head coil repositioning, excellent results can be obtained [5]. At first sight, these results appear to contradict theoretical work suggesting cross-calibration needs to be accurate to “within 1.4 mm” [6] or “substantially below 1 mm and 1°” [7]. The purpose of this work was to build tools to simulate prospective motion correction in the case of a camera mounted on the head coil, to determine the tolerance in head coil repositioning, and to understand the discrepancy between previously published results.

Methods: *Simulator* – Software was written to simulate prospective motion correction using a 3D head model derived from each patient’s 3D MRI data, recorded or simulated motion, the camera pose, and cross-calibration errors (Fig. 2, left). This enables the evaluation of prospective motion correction performance for various errors in camera repositioning.

Motion correction metric – To aid interpretation of the effects of motion on the MR imaging process, we define a new metric: the mean voxel displacement, or MVD. This is used to quantify motion by deriving a single number from detected/residual motion. The MVD is calculated by summing the vector magnitude displacement of all n voxels in the 3D head model and dividing by n.

In vivo threshold determination – To relate the quantitative MVD metric to the quality of the MR images and determine a threshold for “good” motion correction, three volunteers were scanned multiple times on a 3T MR system (GE Healthcare). For each scan, they were asked to perform head motion with varying range. Motion data was obtained from an optical tracking system for each scan to quantify the MVD. By visually inspecting the MR images, a threshold was determined for the required reduction in MVD, expressed as a percentage. A percentage reduction is used rather than an absolute MVD value, so that the threshold is independent of the motion magnitude or the imaging sequence.

Mechanical tolerance determination – The simulator, MVD metric and threshold were used in combination to determine the acceptable mechanical tolerance for repositioning of the head coil and camera. Rotation errors were fixed at 1.5°, since in our experience rotation of the head coil is already tightly constrained, but all three translations were left as free parameters.

Results: Fig. 3 shows example results from the in vivo scans used to determine the MVD threshold. Visual inspective of images shows a reduction in MVD of 72% is unacceptable, but 80% or above produces clinically acceptable results for imaging with T1/T2 weighted contrast. Allowing for a safety margin, we propose a target of 90% MVD reduction. Fig. 4 shows the mechanical tolerance results, based on this threshold of 90%: translation errors, simultaneously applied in x, y and z directions, can be up to 6 mm, when rotation errors are set to 1.5°.

Discussion: The results indicate that good motion correction performance can be obtained despite cross-calibration errors of several millimeters. The discrepancy between this and the tighter tolerances given in [5, 6] occurs because here the threshold for ‘acceptable’ motion correction is a 90% reduction in voxel motion, whereas previous work attempts to keep residual artifacts below the noise floor, using motion of a worst-case voxel. Thus, our results complement, rather than contradict previous work. Our proposed MVD threshold has several advantages: it uses patient-specific data to avoid head geometry assumptions; it is not dependent on motion magnitude, because it uses a percentage improvement; and a practical threshold is set to make a substantial difference to any given exam, which is the end goal of prospective motion correction.

Conclusion: For practical purposes, camera repositioning errors of several millimeters do not prevent good optical prospective motion correction results.

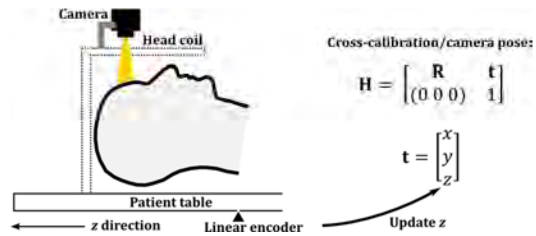

Fig. 1: Camera system mounted on head coil and used for prospective motion correction. The encoder is used to update the cross-calibration matrix if the scanner table moves.

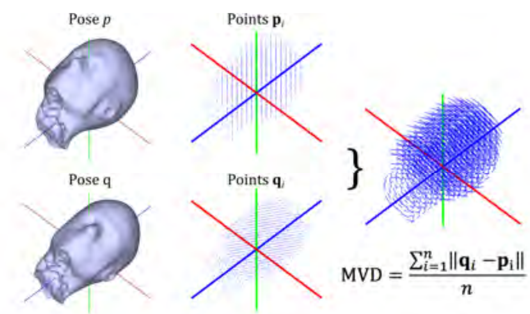

Fig. 2: Simulation environment and MVD calculation. Point clouds representing all n voxels inside the head model are used to calculate the ‘mean voxel displacement’ (MVD) between consecutive time points (p and q, here). This is summed over the entire scan to serve as a metric for the amount of motion that occurred or remained uncorrected.

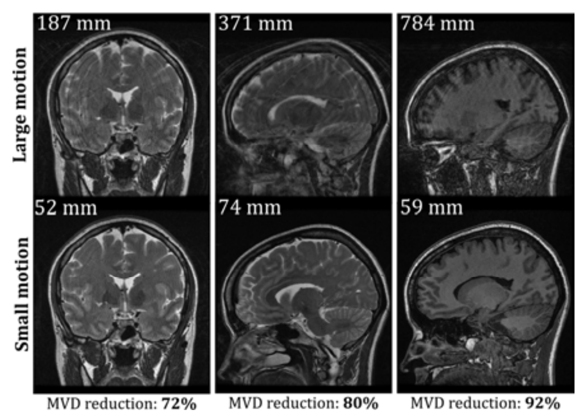

Fig. 3: Example in vivo measurements with varying amounts of motion (mean voxel displacement, MVD, in white) used to determine the MVD reduction requirements for acceptable prevention of motion artifacts. A reduction in MVD of ~90% appears more than sufficient for useful motion correction.

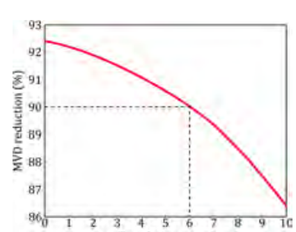

Fig. 4: Motion reduction after prospective correction vs errors in camera pose. MVD reduction of 90% can be achieved with errors of 6 mm or less, indicating that it is practical to use the table position encoder, despite its limited accuracy.

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