Motion Degradation in 3D µMRI of Trabecular Bone: Relevance to Quantitative Analysis of Clinical Data

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INTRODUCTION: Three-dimensional µMRI acquisition and processing techniques enable direct visualization and quantification of trabecular bone (TB) architecture in response to aging or drug treatment of osteoporosis [1]. At acquisition times on the order of 10-15 minutes, motion degradation can be a significant source of error in high-resolution µMRI of trabecular bone (TB) as it leads to blurring of the TB microstructure resulting in a loss of sensitivity and reproducibility of the structural parameters [2]. The resulting errors in the derived structural parameters can mask treatment effects. Sub-millimeter in–plane translational motion can be effectively detected using navigator-projections and retrospectively corrected in the high resolution images [3]. Previously, the qualitative and quantitative effects of translational motion displacements were studied on one high quality *in vivo* TB image derived with the 3D Fast Large Angle Spin Echo (FLASE) [4] pulse sequence by applying various simulated and retrospective *in vivo* trajectories to induce motion degradation [5]. The results demonstrated consistently lower image quality and alterations in structural and topological parameters with increased translational displacements. Here, we sought to compare the effects of 20 unique retrospectively derived translational motion trajectories on the change in image quality and structural parameters in TB micro-images of the distal tibia from two groups (10 each) of normal individuals who were stratified in each group according to their age range. We hypothesized that motion degradation applied to each individual data-set would eventually lead to a reduction in significance for differences in the quantitative parameters between two groups who differ in their TB architecture, thereby masking the full extent of the underlying differences in bone integrity between these groups.

METHODS: A retrospective analysis employing virtual bone biopsy processing [6] was undertaken on motion-free 3D FLASE images (voxel size of 137x137x410 μm^3) of the left distal tibia of 20 healthy individuals (age range, 26-51 years) acquired at 1.5T (Siemens Sonata). The subjects were divided into two groups of 10: 1) Young (19-26 years, median=24.5 years) and 2) Middle-aged (40-53 years, median=44 years). A one-way ANOVA indicated that the differences in TB parameters quantifying scale and topology between the two groups for parameters such as bone volume fraction (BVF, 7%), surface-to-curve (S/C) ratio (17.3%) and erosion index (EI, 20.4%) were statistically significant ($p<0.05$). Each of the 20 images was then subjected to one of 20 randomly-assigned, uniquely different x- and y- translational motion trajectories derived from retrospective analysis of the navigator-based data correction from patient FLASE scans. The randomly selected trajectories ranged from -0.5 to +9 pixels along x and -0.3 to +12.5 pixels along the y axis. Each point within an input motion trajectory (460 total y-phase encodings in the FLASE acquisition) represented the average shift for a given 2 second period during a scan. The x- and y- shifts were applied as phase factors to the k-space data of the original scans resulting in motion-corrupted images upon inverse Fourier transformation. All original and motion-degraded images were graded by 3 raters for motion severity on a scale of 1-10 (1: worst, 10: motion-free) in a blinded fashion. Additionally, an objective image quality focus criterion, the normalized gradient squared (NGS) [7] was also computed for each image followed by masking of the tibial TB region on the motion-induced images. Comparisons of the TB parameters were performed thereafter between the original and motion-induced data using a one-way ANOVA.

RESULTS: The NGS values of motion-degraded images were consistently reduced (3.5% to 10%, $p<0.001$) relative to the original images in all 20 cases. Similarly, mean motion scores upon motion-induction were also lower signifying blurring of the TB microstructure; albeit to a greater extent (4% to 68% decreases, $p<0.001$) compared to the NGS values. Nonetheless, a strong correlation was observed between the percent differences of both image quality measures (**Figure 1**). On average, motion degradation resulted in significant reductions in BVF (8% to 9%) and S/C (24% to 29%) and increases in EI (32% to 40%) within both groups ($p<0.001$). **Figure 2** displays representative images and the applied motion trajectories for comparison between two individuals, a young (A, 26 years) and a middle-aged (B, 51 years) subject, where motion-induction led to a reduction in both, the mean motion score and NGS values for both data-sets. A comparison of the percent differences in TB structural parameters of both subjects before and after motion-induction (**Figure 2C**) by different trajectories revealed that a strong age-related effect in the parameters that was apparent in the motion-free images (decreases in BVF and S/C (5% to 16%) and an increase in EI (18%)) were substantially attenuated following motion degradation. Similar levels of differences in the means were also observed in other comparisons between the two groups. Overall, the difference in mean BVF values between the young (11.12±0.61%) and the middle-aged (10.30±0.68%) group in the original data (7.6% difference, $p=0.009$) was reduced (6.3% difference) and significance was lost ($p=0.06$). Similar changes were also detected for S/C and EI following motion degradation between both groups (**Figure 3**).

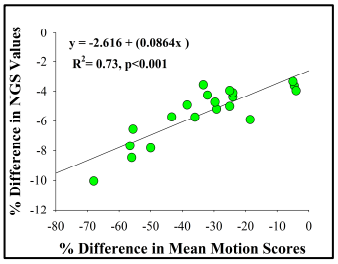

Figure 1: Comparison of percent differences in mean motion and in NGS values between the original and motion-corrupted images of 20 healthy young and middle-aged subjects.

CONCLUSION: Quantitative TB structural measures are highly sensitive to subtle motion-induced degradation and can mask group differences and potentially treatment effects in patient data. The level of translational motion displacements does not have to be severe with aggregate displacements during the scan on the order of 2-3 pixels (300-400 µm) sufficient to blur images and render them unsuited for analysis. Further work is needed to identify locations in K-space where the occurrence of translational displacements is particularly critical. A more detailed framework should incorporate the effects of rotational displacements on TB microarchitecture.

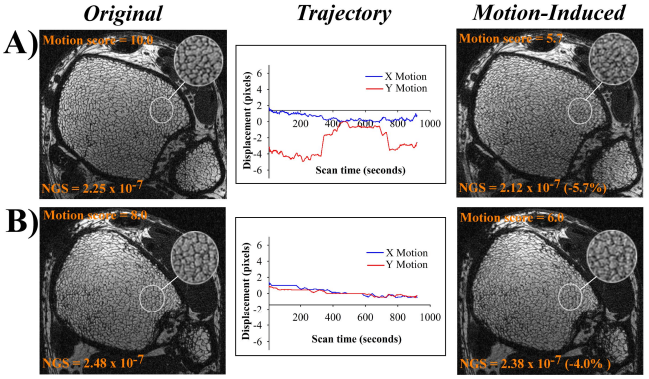

Figure 2: Comparison of images (**A**-26 year-old; **B**-51 year-old) and percent differences in the TB measures (**C**) between the two subjects before and after motion degradation.

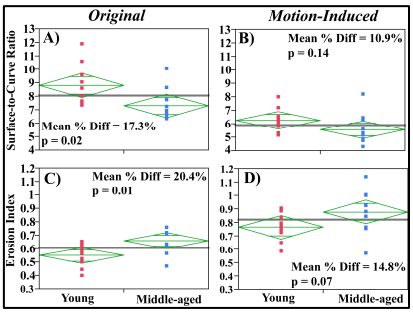

Figure 3: Scatter-plots of surface-to-curve ratio (A, B) and Erosion index (C, D) demonstrating the masking of healthy age-related differences after motion induction in two groups of 20 subjects. Diamonds highlight the 95% CI about the means.

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ACKNOWLEDGEMENTS: NIH RO1 AR41443, RO1 AR53156, RO1 DK75648