

Evaluation and Correction of Noise and Resolution Induced Errors in Quantitative Trabecular Bone μ MRI

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Introduction

Osteoporosis, an osteodegenerative disease disturbing the dynamic equilibrium of bone formation and resorption, primarily manifests itself in a reduction in bone mass, commonly detected using dual-energy X-ray absorptiometry. However, this technique provides no information on actual trabecular structure, which plays an important role in determining the overall mechanical strength of the bone [1]. In order to detect the effects of bone loss on the structure of trabecular networks and resulting changes in bone mechanical strength, a technique that combines magnetic resonance micro-imaging (μ MRI) and digital image processing that is capable of non-invasively quantifying trabecular structure and topology has recently been developed [2, 3]. However, this technique faces several challenges in order to accurately derive bone structure from μ MR images in the limited spatial resolution regime of in-vivo imaging and in the presence of noise. The objective of the present work was to evaluate the errors incurred from limited resolution sampling and the presence of noise, and to explore possible means to correct for such errors.

Materials and Methods

To evaluate how VBB image processing algorithms are affected by these factors, in-vivo μ MR images of trabecular bone were simulated from ex-vivo μ CT scans of human cadaveric bone (Figure 1). Nine bone specimens extracted from the femur, lumbar vertebrae and tibia of human donors were scanned by μ CT at a voxel size of $21 \times 21 \times 22 \mu\text{m}^3$. These images were segmented to isolate trabecular bone, inverted to mimic MR signal intensity, and downsampled in the spatial frequency domain to a spatial resolution of $126 \times 126 \times 396 \mu\text{m}^3$ to emulate a voxel size achievable at 1.5T. Using this dataset, the effects of image noise on the structural parameter calculations were examined first, by maintaining a voxel size of $126 \times 126 \times 396 \mu\text{m}^3$ and superimposing varying amounts of Rician noise to attain an SNR range of 6 to 16. The resulting images were then analyzed by subjecting them to a cascade of processing steps that involve sinc interpolation (by a factor of $3 \times 3 \times 6$) and skeletonization to quantify trabecular structure by digital topological analysis [4], and errors in the apparent structural parameters caused by image noise were evaluated. We hypothesized that the apparent structural parameters at any SNR are linearly related to the “true” parameter values calculated from the original noiseless images. Linear fits were applied to each set of parameters calculated at a given SNR in relation to the same parameter calculated from the noiseless images, resulting in slopes and intercepts corresponding to each simulated SNR. The change in structural parameter values (represented by the behavior of these linear relationships) with respect to image noise was quantified as two spline curve fits for each parameter, one fitting all the slopes of each parameter’s linear fits at all simulated SNRs, and the other fitting the intercepts. Parameters were then corrected by linear transformation, using the curve fits to determine approximate correction slopes and intercepts at any SNR.

The effects of image resolution on parameter calculation were similarly investigated. The simulated μ MR images were downsampled in the transverse plane to various resolutions by zeroing high-frequency data in k-space, generating a set of images with spatial resolutions varying from $126 \times 126 \times 396 \mu\text{m}^3$ to $378 \times 378 \times 396 \mu\text{m}^3$. The relationship between resolution and parameter values was approximated similarly to the resolution simulations, and consequently the same correction methods were employed. The corrected structural parameters of both the noisy and reduced resolution images were then compared to the uncorrected parameters to assess the efficacy of the linear transformation corrections.

Results

Figures 2 and 3 show that the apparent structural parameters predicted to occur at a given SNR are indeed linearly related to the “true” parameter values calculated from noiseless images, although this relationship weakens with decreasing SNR and resolution. The data further show that parameters derived at decreased SNR and resolution could be corrected by linear transformations derived from the aforementioned linear relationships. These corrections significantly decreased the effect of noise and resolution on the accuracy of structural parameter calculation. For example, corrections applied to the surface-surface junction density parameter reduced error by approximately 50% in the SNR 8 – 10 range (Figure 4), showing a significant reduction in noise-induced error after correction.

Conclusion

It is concluded that even though image voxel size and limited SNR characteristic of in-vivo structural imaging affect structural parameters, it is possible to retrospectively correct for these differences and thus normalize the data. These corrections would be a crucial step in comparing VBB analyses across images with varying voxel sizes and SNR, or in normalizing parameters calculated from a single image with spatially varying noise.

References

- [1] Seeman E, et al., *N Engl J Med* **354** 2250-61 (2006). [2] Wehrli FW, et al., *Proc IEEE* **91** 1520-42 (2003). [3] Wehrli FW, et al. *NMR Biomed* **19** 731-64 (2006). [4] Saha PK, et al., *Int J Imag Syst Tech* **11** 81-90 (2000)

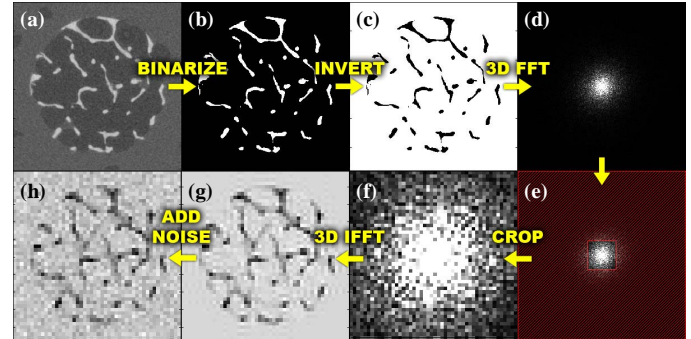


Figure 1. Illustration of processing sequence: ex-vivo μ CT (a), threshold segmented into binarized image (b), inverted to mimic MRI signal intensity (c), 3D FFT into k-space (d), high-frequency data selected (e), low-pass filtering applied (f), 3D inverse FFT to produce μ MRI resolution image (g), superimposed with noise (h).

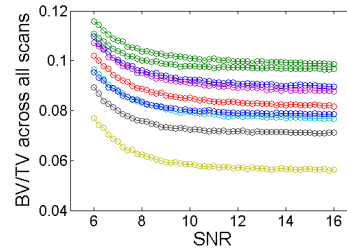


Figure 2. Bone volume fraction (bone volume/total volume, or BV/TV) as a function of SNR. Each curve represents a different specimen.

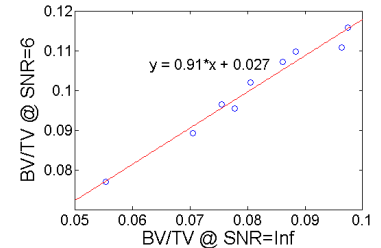


Figure 3. Linear relationship between structural parameter “BV/TV” (bone volume fraction) at SNR=(N=6) and value at SNR=Inf.

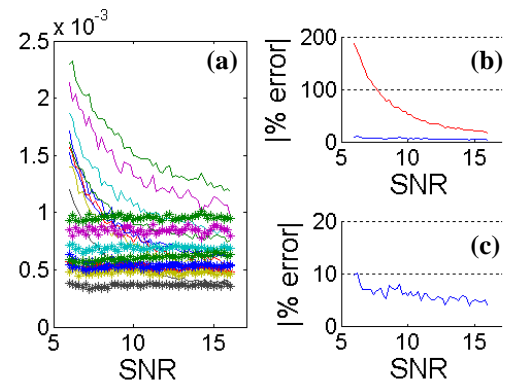


Figure 4. Correction for varying SNR of surface-surface junction density (SS density) and correction accuracy: (a) SS density before correction (line), corrected SS density (asterisks); (b) errors in SS density calculation induced by noise (red) and after correction (blue); (c) error in SS density calculations after correction.