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Wavelet Based Characterization of ex vivo Vertebral Trabecular Bone Structure with 3T MRI compared to MicroCT

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Abstract—**Trabecular bone structure and bone density contribute to the strength of bone and are important in the study of osteoporosis. Wavelets are a powerful tool to characterize and quantify texture in an image. In this study the thickness of trabecular bone was analyzed in 8 cylindrical cores of the vertebral spine. Images were obtained from 3 Tesla (T) magnetic resonance imaging (MRI) and micro-computed tomography (μCT). Results from the wavelet based analysis of trabecular bone were compared with standard two-dimensional structural parameters (analogous to bone histomorphometry) obtained using mean intercept length (MR images) and direct 3D distance transformation methods (μCT images). Additionally, the bone volume fraction was determined from MR images. We conclude that the wavelet based analyses delivers comparable results to the established MR histomorphometric measurements. The average deviation in trabecular thickness was less than one pixel size between the wavelet and the standard approach for both MR and μCT analysis. Since the wavelet based method is less sensitive to image noise, we see an advantage of wavelet analysis of trabecular bone for MR imaging when going to higher resolution.**

Keywords— **Magnetic Resonance Imaging, MicroCT, Osteoporosis, Trabecular Thickness, Wavelets**

I. Introduction

Osteoporosis is a widely prevalent skeletal disorder associated with a reduction in bone mass and a deterioration of bone structure [1]. Studies have indicated that bone mineral density alone may have limitations in assessing the strength of cancellous bone and that the trabecular architecture is an important factor in determining bone strength. Traditionally, trabecular structure has been assessed from two-dimensional (2D) analysis of histological sections obtained from iliac crest biopsies.

Multiple approaches to characterize the micro structure of trabecular bone in vivo using MRI have been attempted. This is a challenging task, especially since typical trabecular dimensions (50 to 200 μm) is on the order of the currently achievable resolution (~150 to 200 μm) in state of the art in vivo MR imaging. This is due to signal to noise (SNR) constraints and thus resolution limitations give rise to partial volume effects and results in an overestimation of trabecular thickness. Consequently, structural bone parameters derived from MR images are usually labeled as *apparent* (app.) values, which are similar but not equal to their histomorphometric counterparts. However, initial studies comparing MR-derived 2D structure measures to 20 micron μCT images show that these structure measurements contribute to the assessment of trabecular bone strength [2].

The established method of determining the two dimensional structural parameters analogous to bone histomorphometry applies the mean intercept length (MIL) technique previously described in detail [3]. This approach features bone / bone-marrow binarization of the coil-inhomogeneity corrected MR image. However, the binarization process of the image is a non trivial task and requires the determination of two reference intensity levels (one for bone and one for bone-marrow) due to the above mentioned partial volume effects in the image voxels. Determination of dual reference thresholds is prone to inaccuracy and a great amount of information is lost by reducing the 16 bit MR image to a 1 bit binarized image.

To overcome this limitation, we present a wavelet based approach [4] to characterize the mean thickness of the trabecular network in bone. Wavelet analysis is a new tool for characterizing complex structures on a pixel level without a binarization step and thus could provides more insight into bone structure. Furthermore, it has been demonstrated that wavelets are capable of capturing the structure of interest under extremely noisy conditions [4]. In this work we analyzed the trabecular bone structure in eight MR images obtained from cylindrical human vertebral bone cores with the conventional 2D MIL approach and also with 2D wavelets. As a reference, we additionally acquired μCT images from the same eight specimens. Due to the isotropic voxel size, a three dimensional (3D) analysis was conducted. The standard approach to determine the structural bone parameters in μCT features 3D distance transformation methods (DT) [5]. Accordingly, the applied wavelet transformation in μCT images was also conducted in 3D.

II. Methodology

A. Specimen Preparation

Eight cylindrical cores were obtained from human vertebral bone with an 8 mm inner diameter diamond tipped coring drill bit mounted on a drill press. The resulting cores ranged from 10 mm to 18 mm in length. A diameter of 8 mm allowed the cores to be mounted in the μCT machine and imaged at the desired spatial resolution. Additionally, this diameter allowed for adequate preparation for MR imaging. In preparation for MR scanning, each core was defatted in a 10% solution of an enzyme-active powdered detergent and then mounted in a customized container.

The cores were then immersed in 0.5 volume-% gadolinium-DTPA-doped water to simulate the contrast found between yellow marrow and trabecular bone. After that, the container with the specimen was placed in a vacuum pump and degassed prior to imaging to reduce artifacts arising from differences in susceptibility between air, solvent, and bone.

B. Image Acquisition

MR images were obtained using a four-element phased array coil at 3 T (Nova Medical, Wilmington, MA) on a Signa MRI system (General Electric, Milwaukee, WI). High resolution coronal images were acquired using a 3D fast gradient echo (FGRE) sequence. The imaging parameters used are shown in Table 1. The MR image containing the specimen as subimages was divided into eight smaller volumes (99 × 99 × z pixels), where the number of slices (z) varied between 48 and 128 depending on the length of the core.

After MRI acquisition, μCT images were acquired (Scanco Medical AG, Bassersdorf, Switzerland) with isotropic resolution of 16 μm. The μCT images had a matrix size of 1024 × 1024 pixels and up to 1200 slices depending on the length of the specimen.

TABLE I
MRI Scanning Parameters at 3T

Parameter	*3 Tesla*
TE/TR	23.5 / 11.1 ms
Flip angle	20°
Bandwidth	15.63 Hz/pix
In plane resolution	0.117 mm
Slice thickness	0.3 mm
Imaging time	30 min

C. Standard Measurement of Structural Parameters

From the MRI dataset 2D structural parameters analogous to bone histomorphometry were derived using the MIL method based on the plate model for MRI analysis [3]. This method involves the extension of a set of parallel rays across the binarized image at a series of angles (θ). Structural parameters derived included app.BV/TV (bone volume/total volume) and app.Tb.Th (trabecular thickness).

Determination of app. Tb.Th. begins with counting the number of black (bone) and white (marrow) pixel interfaces that are encountered by a set of parallel rays at a given angle θ. This value is used to determine the mean intercept length (MIL) by taking the ratio of the total area of the black pixels in the ROI versus half the number of edges counted. The overall mean width of the black pixels (app. Tb.Th.) is obtained by taking the average MIL for all angles. App. BV/TV is calculated as the total number of black pixels representing bone over the total number of pixels in the ROI.

For μCT images, only trabecular thickness was determined by the wavelet method, since in this case the BV/TV is obtained by a simple binarization of the image. Determination of Tb.Th. by the direct 3D distance transformation method is accomplished by filling the bone phase of the binarized image with maximal spheres as described in [5] and [6]. The mean diameter of all of the spheres used to fill the bone phase corresponds to the mean thickness of the trabecular network.

D. New Wavelet Approach

Trabecular thickness was also measured using a new 3D wavelet-based filter that was developed to visualize structural features in noisy biological data [4]. The filter's only adjustable parameter is the wavelet "size", which represents a characteristic linear size of the feature of interest, i.e., the trabeculae. The wavelet "size" is measured in pixels, the natural unit to use in image processing. The filter transforms the original spatial distribution of intensities into a spatial distribution of correlations that has the visual appearance of the original image, but with strong highlighting of the regions whose size is similar to the wavelet "size". Wavelet sizes from 1 to 15 pixels were used, thus, each data set generated 15 new data sets, one for each wavelet size.

The wavelet filter is normalized so that the maximum response (correlation) is obtained when the characteristic size of the feature of interest (trabelcular thickness) equals the wavelet size. In order to neglect very weak responses, a global threshold was set automatically equal to the mean of the 15 wavelet responses at each spatial point. Values below this threshold were set equal to zero.

The residual responses were weighted according to their magnitudes and summed in order to get the trabecular thickness at each pixel. The result of this procedure can be interpreted as a map of the trabecular size. The app. BV/TV was determined using this *thickness map* by placing a ROI for each slice. These values were then compared with results from image binarization by means of dual reference intensity threshold described in [3]. The same ROIs were used for both methods.

III. RESULTS

A. MRI measurements

A typical MR image is shown in Figure 1 along with its thickness map resulting from the wavelet transformation described above. The pixel values are indicated on the color bar for each image. The figure shows that the trabeculae are

clearer in the thickness map than in the original image which is blurred by partial volume effects. Since histomorphometric measurements use the MIL approach, they do not result in a thickness map. The app. Tb.Th is here indicated as an average thickness of the trabeculae.

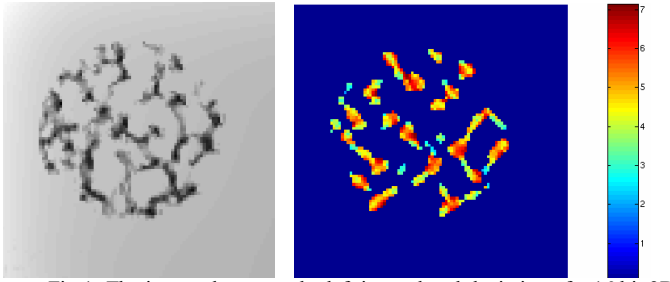

Fig 1: The image shown on the left is a colored depiction of a 16 bit 2D MR grey level image. The resulting wavelet calculated thickness map is shown on the right. The thickness of the trabeculae is depicted in pixel size (see color bar). Maximal thickness found here is 7 pixels.

Comparisons with histomorphometry measurements revealed a smaller mean app. BV/TV (0.28 compared to 0.4) and higher app. TbTh (0.25 compared to 0.24 mm). The difference in mean app.TbTh corresponds to less than one pixel (0.94 pixels). Since the variation in thicknesses found for the trabeculae is very small between the specimen no significant correlation could be was found. Whereas the app. BV/TV values showed a correlation of R=0.51. These results are also evident from Figure 2, where the calculated mean structural parameters are depicted for every specimen.

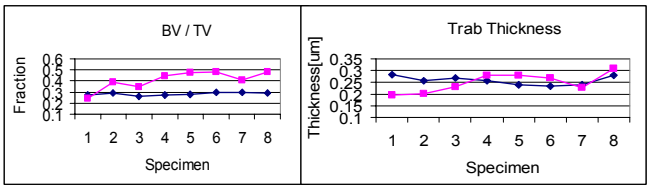

Fig 2: Results for app. BV/TV and app. Tb.Th plotted for each specimen for wavelet (blue) and histomorphometry analysis (pink) . The calculated thickness varies very few and no significant correlation could be determined. Whereas the bone fraction found from the wavelet approach is significantly lower than the app. BV/TV from histomorphometry measurements. However, a correlation factor of R=0.51 was found.

A. MicroCT measurements

As an additional validation of our method, we applied the wavelet transform to µCT images with higher resolution (16 µm) than it is currently achievable with MRI. Figure 3 shows two trabeculae thickness maps resulting from the "gold standard" direct 3D distance transformation and 3D wavelet filtering. The figure shows that the first method is much more sensitive to small changes in trabecular thickness, whereas, the wavelet based method shows less variation and averages the trabeculae thicknesses. However, as can be seen in Figure 4, the difference in calculated thickness is less than one pixel.

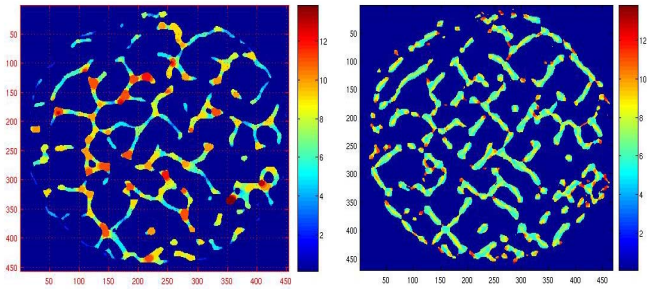

Fig 3: Obtained thickness maps obtained from µCT images with standard 3D-DT (left) and wavelet transformation (right). The resolution of the acquired µCT image permits a very accurate depiction of the trabecular network. The wavelets reveal a more homogenous thickness over the entire image than the standard method does. However, the range of thickness values is between 2 and 12 pixels for both methods (see color bar).

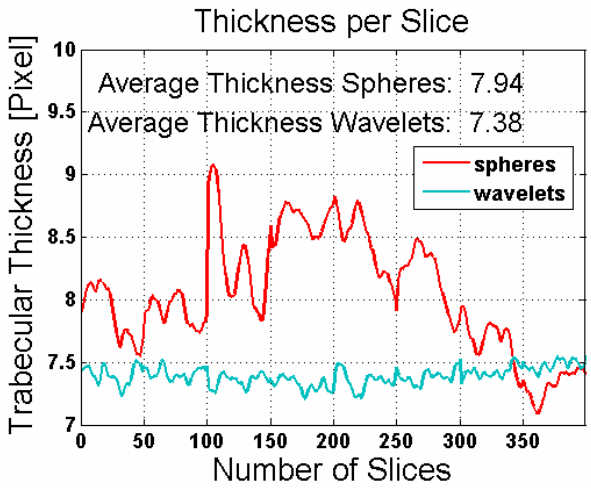

Fig 4: Comparison of averaged trabecular thickness for every slice of one sample specimen. Wavelet determined thickness is more homogeneous over all image slices than the direct distance measurements. However, the thickness difference is only 0.37 pixels.

IV. Discussion

In this paper we have presented wavelet based analysis as an alternative approach to characterize trabecular thickness from MR images. We have validated the technique by applying the wavelet transform on high resolution µCT images. Mean values of trabecular thickness were comparable to those obtained using the direct 3D distance transformation method, which is the current "gold standard" for bone analysis in µCT imaging. Differences in mean trabecular thickness values between the two techniques were on the order of one pixel size. However, the wavelet approach resulted in a more even distribution of thickness values. The ranges of values (between 2 and 12 pixels) were similar for both methods.

A possible explanation for the more uniform response of the wavelet approach is that unlike the direct 3D distance measurement technique, it does not operate on binarized images. The standard technique demands a binarized image which can be easily obtained from µCT images by setting one threshold since the histogram of the CT image shows clearly two peaks. The wavelet approach operates on the original image and thus a binarization is not required. As a result, variations in grey levels values over the trabeculae cause variations in the response of the wavelets. This may be overcome by applying wavelets with a different shape e.g. wavelets with a Gaussian kernel. The wavelet kernel best suited to our purpose has to be investigated in more detail in future studies.

Since high resolution CT is an imaging technique which involves high radiation, it is not suitable for in vivo human measurements of trabecular bone. The imaging method of choice for in vivo bone measurements in humans with no radiation is MRI. However, the currently achievable resolution is not sufficient to resolve the trabecular structure accurately. Current analysis methods [3] require binarized images. Because of partial volume effects, it is not possible to separate MR images with a simple threshold into bone and bone-marrow pixels. Wavelets do not require a binarized image. Furthermore wavelets are relatively insensitive to noise [4] and are thus less prone to the lower SNR in MR images. Comparisons with the standard MIL method revealed a difference in trabecular thickness of less than one pixel.

Furthermore, there was a correlation of 0.51 in app. BV/TV measurement yielded by MIL method and that obtained from the thickness map in wavelet analysis.

V. Conclusion

In this work we presented a wavelet transform approach for the analysis of the thickness of trabecular bone. A validation of the method with high resolution µCT images showed the accuracy of the method compared to standard analysis. Applying this method on MR images, the results found were comparable to histomorphometric analysis. In summary we showed that the wavelet technique is a useful tool to analyze trabecular structure in bone. Further investigations have to show if optimized wavelet kernels could improve the accuracy compared to the standard 3D DT. It has also to be proven if the presented wavelet approach has any advantage over current used analysis. Especially for very noisy MR images with increased resolution (in the order of the trabeculae) wavelet analysis could be the method of choice to depict the trabecular thickness more accurately.

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