Trabecular Bone Structure of the Calcaneus: Comparison of high resolution MR Imaging at 1.5T and 3T using MicroCT as a standard of reference

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Background: Bone – Basic

- Bone cells – function
- Bone remodeling cycle – resorption & formation
- Bone remodeling and osteoporosis:
  - Reduction in bone mass
  - Deterioration of bone micro-architecture
    \[\downarrow\]
    Changes in biomechanical strength
    \[\downarrow\]
    FRACTURES
Background: Bone – Basic

- Bone structure:
  - trabecular bone = cancellous
  - cortical bone = compact

- How to measure in vivo the strength of the trabecular bone?

- How to depict and quantify the trabecular bone micro-architecture?
Background: Bone – Basic

- **Strength of trabecular bone**: Density + Quality
  - **Density**
    - Explains 60-90% of bone strength
    - Non-linear relationship: strength $\propto$ (density)
  - **Architecture**
    - orientation
    - thickness / spacing of trabeculae
    - connectivity
  - **Composition**
    - mineralisation
    - collagen content
  - **Bone remodeling**: formation / resorption
    - microdamage
    - turnover
    - cell viability

Background

Depiction of trabecular bone micro-architecture

Basic, exp. Techniques

- Scattered Electron Microscopy
- Histomorphometry

Recent Techniques

- Micro-Computed Tomography
- HR-MRI

⇒ Limitations at 1.5 T: SNR and spatial resolution
BACKGROUND

- Depiction of Trabecular Bone Architecture using HR-MRI

- Limitations at 1.5T:
  - Signal to noise ratio (SNR)
  - Spatial resolution
PURPOSE OF THE STUDY

• Comparison of the depiction of the trabecular bone architecture at 1.5T and at 3T.

• Correlation of MR derived structure parameters versus those obtained with Micro-CT.

• Correlation between Tb parameters obtained from human calcaneus at 1.5T and at 3T with bone mineral density (BMD) data.
METHODS:
Calcaneus Specimens

- 40 calcaneus specimens:
  - 20 women (age: mean ± SD, 76.7 years ± 10)
  - 20 men (age: mean ± SD, 85.4 years ± 9)

- Fixed in formalin

- Embedded in paraffin
METHODS: MR IMAGING - Sequence Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1.5 T (FGRE)</th>
<th>3 T (FGRE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR (ms)</td>
<td>19</td>
<td>18.5</td>
</tr>
<tr>
<td>TE (ms)</td>
<td>4.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Flip angle (degree)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Bandwidth (kHz)</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Spatial resolution (µm)</td>
<td>156</td>
<td>156</td>
</tr>
<tr>
<td>T acquisition (min)</td>
<td>8:11</td>
<td>7:34</td>
</tr>
</tbody>
</table>
METHODS:

MicroCT

- MicroCT 20 scanner (Scanco Medical, Bassersdorf, Switzerland)
- Spatial resolution: 26 µm
- Cylindrical cores (diameter: 10 mm; length: 10 mm)
METHODS: IMAGE ANALYSIS FOR HR-MRI

- Spatial coregistration of images obtained at 1.5T and 3T (Analyze Software)
- Definition of 20 identical ROIs for each specimen at 1.5T and 3T used for:
  - SNR = SI / SD background noise
  - Structural analysis
METHODS: IMAGE ANALYSIS FOR HR-MRI

Structure analysis:

- correction for coil inhomogeneities* with a low-pass filter (LPF) based coil sensitivity

- binarization of the image into bone and marrow phases**

* Newitt et al, Osteoporosis Int 2002;13 (4): 278-87
** Majundar et al, J Bone Miner Res 1997;12: 111-8
Thresholding technique with dual-threshold algorithm

Image with coil correction

Corresponding binarized image
Measures of structural parameters* analogous to histomorphometric parameters in the binarized ROIs:

- app. BV/TV
- app. trabecular number (Tb. N)
- app. trabecular thickness (Tb. Th)
- app. trabecular spacing (Tb. Sp)

RESULTS

- **Qualitative analysis:**
  better depiction of Tb bone structure at 3T than at 1.5T

- **Quantitative analysis:**

- Correlation between App.Tb.BV/TV at 3T and BMD $>\text{Correlation between App.Tb.BV/TV at 1.5T and BMD}$
  
  ($r = 0.786 \text{ vs } r = 0.731$)
RESULTS
HR-MR images from calcaneus specimens acquired with FGRE sequence at 1.5T (A, C) and at 3T (B, D): A and B illustrate an osteoporotic specimen obtained from a donor with vertebral fractures in comparison with a normal specimen depicted by C and D obtained from a donor without vertebral fractures.
RESULTS

Representative MR images obtained at 1.5T (B) and 3.0T (A). The circle indicates the corresponding region of the µCT image (C).
### RESULTS

<table>
<thead>
<tr>
<th></th>
<th>1.5 T</th>
<th>3.0 T</th>
<th>Correlation 1.5T MicroCT (R)</th>
<th>Correlation 3 T MicroCT (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SNR</strong></td>
<td>12.9 ± 2.7</td>
<td>16.3 ± 2.4</td>
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</tr>
<tr>
<td><strong>App. BV/TV</strong></td>
<td>0.28 ± 0.04</td>
<td>0.41 ± 0.04*</td>
<td>0.68</td>
<td>0.87*</td>
</tr>
<tr>
<td><strong>App. Tb. N.</strong></td>
<td>1.54 ± 0.15</td>
<td>1.84 ± 0.11*</td>
<td>0.76</td>
<td>0.79</td>
</tr>
<tr>
<td>(mm⁻¹)</td>
<td></td>
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<tr>
<td><strong>App. Tb. Sp.</strong></td>
<td>0.47 ± 0.07</td>
<td>0.32 ± 0.04*</td>
<td>0.72</td>
<td>0.87</td>
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<td>(mm)</td>
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<tr>
<td><strong>App. Tb. Th.</strong></td>
<td>0.18 ± 0.02</td>
<td>0.22 ± 0.02*</td>
<td>0.57</td>
<td>0.76*</td>
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<td>(mm)</td>
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Values are means ± SD (n = 40).

* *P = 0.001 compared with 1.5 T measure by paired t test*
Linear regression was used to obtain the correlation between the measures.

app. BV/TV (Bone Volume Fraction):
\[ r = 0.68 \text{ at } 1.5\text{T} / r = 0.87 \text{ at } 3\text{T} \]

app. Tb.N (Trabecular Number):
\[ r = 0.76 \text{ at } 1.5\text{T} / r = 0.79 \text{ at } 3\text{T} \]
app. Tb.Sp (Trabecular Separation):
\( r = 0.72 \) at 1.5T / \( r = 0.87 \) at 3T

app. Tb.Th (Trabecular Thickness):
\( r = 0.57 \) at 1.5T / \( r = 0.76 \) at 3T
• Improvement of the depiction of Tb microarchitecture

• SNR (3T) : 26% higher than SNR (1.5 T)

• Higher Correlations of the structure parameters with MicroCT at 3T than at 1.5T

• HR-MRI at 3T: increase of susceptibility artifacts

• Optimized depiction of trabecular bone for research and potentially for clinical indications
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