Prediction of bone mechanical properties using quantitative MRI

E. Lammentausta[1], M. A. Hakulinen[1], I. Kiviranta[2], J. S. Jurvelin[1,3], M. T. Nieminen[4]

[1]Department of Applied Physics, University of Kuopio, Kuopio, Finland, [2]Department of Orthopaedics and Traumatology, Jyväskylä Central Hospital, Jyväskylä, Finland, [3]Department of Clinical Physiology, Kuopio University hospital, Kuopio, Finland, [4]Department of Diagnostic Radiology, Oulu University hospital, Oulu, Finland

INTRODUCTION

Trabecular bone is porous tissue with a three-dimensional lattice of trabecular plates and fluid-like bone marrow. The mechanical properties of trabecular bone depend on its mineral density and internal structure [1]. Previously, a significant relationship between T2* relaxation time of trabecular bone and bone mineral density has been established [2]. Earlier studies also suggest that trabecular structure can be evaluated from MRI images [3]. The objective of the present study was to characterize the interrelationships between MRI, pQCT and mechanical parameters of human trabecular bone. Especially, we aimed to reveal if a combination of MRI parameters can improve the prediction of density and mechanical properties of trabecular bone.

METHODS

Six locations of human cadaveric patellae (N=14, age 55±18) were investigated. MRI and CT visible markers were used for localization between the different modalities. A total of 84 regions were analysed by using MRI and pQCT methods, and 46 samples were tested mechanically.

For all MRI measurements, a clinical 1.5 T scanner (GE Signa, GE Healthcare, Milwaukee, WI, USA) was used. T2* measurement (multi-slice gradient-echo sequence, TR=100ms,6 TEs between 4.7-28ms, flip angle=30°, in-plane resolution 0.313mm, 3-mm slice thickness) was performed for three slices of each patellae, with two areas of interest on each slice. A 7x7mm region of interest (ROI), localized into the trabecular bone at the site of each marker, was analysed. A multi-slice gradient echo sequence (TR=30ms, TE=4ms, flip angle=40°, in-plane resolution 0.234mm, 1-mm slice thickness, 40 consecutive slices) was used to obtain images over the entire patellar bone for structural assessment. A 7x7x7mm volume of interest (VOI) was assessed, having the centremost slice at the location of the T2* measurements. The apparent bone volume fraction (app.BV/TV) of each location was calculated after binarizing selected regions [4].

Bone mineral density (BMD) was measured by using a clinical peripheral quantitative computed tomography scanner (pQCT, 58kV, 0.175mA, in-plane resolution 0.200mm, 0.5-mm slice thickness; XCT2000, Stratec, Birkenfeld, Germany). The resulting images were binarized and the apparent bone area fraction (app.BA/TA) was determined for the area of interest.

For mechanical testing, cylindrical samples (dia. = 7mm, thickness = 7mm) were isolated from the sites of MRI and pQCT analyses, and tested destructively (Instron FastTrack 8874, Instron, Norwood, MA, USA). The testing protocol included a 2-min equilibration of the sample under a pre-stress of 10N, five non-destructive dynamic cycles (0.5% strain) and destructive compression to 5% strain. The linear region of the stress-strain-curve was analysed to determine Young's modulus (E_s). Yield stress and maximum compressive stress (ultimate strength) were also calculated [5].

RESULTS

All parameters showed a considerable variation among the bone samples (Table 1). Statistically significant linear correlations were demonstrated between MRI, mechanical and pQCT parameters in human patellar trabecular bone (Table 2). The prediction of BMD, yield stress and maximum stress were further improved after combining T2* and MRI-derived apparent BV/TV into a linear model. After combining BMD and pQCT-derived apparent BA/TA, respective improvement was not obtained.

Table 1. Mean (±SD), minimum and maximum values of MRI, pQCT and mechanical parameters.

	Mimimum	Maximum	Mean±SD
app.BV/TV	0.13	0.54	0.32±0.08
T2* [ms]	4.52	12.51	6.26±1.05
app.BA/TA	0.18	0.53	0.28±0.07
BMD [mg/cm^3]	192.3	665.6	387.6±101.7
Es [MPa]	101.2	1361.2	489.4±294.5
Yield Stress [MPa]	2.04	17.62	8.04±3.77
Max. Stress [MPa]	2.57	21.83	9.33±4.45

Table 2. The linear correlation coefficients between MRI, PQCT and mechanical parameters and model fit coefficient of a model including a linear combination of MRI parameters (T2* and app.BV/TV) and a constant.

	pQCT Parameters		Mechanical Properties		
	BMD	app.BA/TA	E_s	Yield Stress	Max. Stress
app.BV/TV	0.56**	0.51**	0.32*	0.46**	0.40**
T_2*	-0.31**	NS	NS	-0.34*	-0.33*
Linear Model	0.60**	0.51**	0.33*	0.50**	0.54**
BMD	-	0.82**	0.44**	0.61**	0.64**
app.BA/TA	0.82**	-	0.36*	0.44**	0.49**
N of samples	84	84	46	46	46

NS - not significant, * $p < 0.05$, ** $p < 0.01$

DISCUSSION

The present results demonstrate the feasibility of MRI methods in evaluating trabecular bone density and structure. The prediction of bone composition and the mechanical properties can be further improved by combining two MRI methodologies developed for the assessment of trabecular bone. However, quantitative parameters as calculated from pQCT images were still more effective in predicting the mechanical properties of trabecular bone as compared to MRI. The MRI results may be further improved by using a higher imaging resolution, thinner slices as well as dedicated sequences used to maximize the signal from bone and to minimize susceptibility artefacts. [6].

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