Improved assessment of vertebral cortex thickness by means of analytical deconvolution of radial bone mineral density distributions

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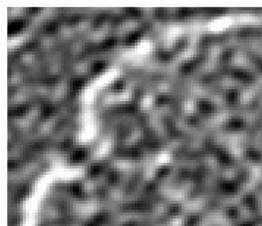[2]Osteoporosezentrum Hamburg–Neuer Wall, Hamburg, Germany
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Background

Assessment of bone stability using computed tomography data requires – besides densitometric parameters – an accurate estimation of the cortical thickness, which in QCT and to a lesser extent also in HRQCT is biased by the partial volume effect and the CT systems modulation transfer function (MTF).

In HRQCT the spatial resolution is, due to an estimated gaussian point spread function (PSF) with a full-width at half-maximum (FWHM) of $(0{,}97\pm0{,}10)$mm $(\delta=0{,}41\pm0{,}04)$, significantly reduced compared to the actual voxel size and even compact structures are broadened, as can be seen in the figure on the right.


Materials and Methods

We analysed 12 excised human vertebrae embedded in epoxy compound. HRpQCT scans were carried out at the Osteoporosezentrum Hamburg and HRQCT scans at the University Hospital Schleswig-Holstein in Kiel. Image acquisition parameters are listed in table 1.

Table 1	HRpQCT	HRQCT
Device	Scanco Medical XtremeCT	Siemens Somatom 64
Voxel Size in mm³	0,082 * 0,082 * 0,082	0,156 * 0,156 * 0,300
Voltage in kV	60	120
Exposure in mAs	190	360
Reconstruction Kernel	standard	B70s

Data Processing with Structural*Insight* 🌱

1. Quality Assurance prior to data analysis
2. Calibration of Hunsfield Units (HU) to mgHA/cc using a simultaneously scanned phantom
3. Template-driven semi-automatic segmentation of the different volumes of interest (VOI): total trabecular volume, ellipse, vertical cortex, upper end plate, lower end plate, foramen and cut pedicles
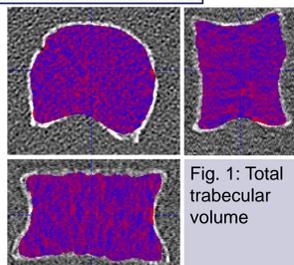
At this point, the segmentation based cortical thickness Ct.Th and the density weighted cortical Thickness wCt.Th can be calculated. The deconvolution-based refinement requires two further processing steps:
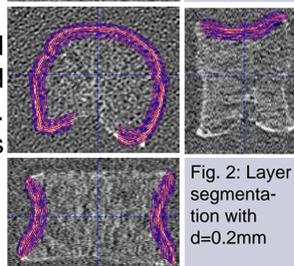
1. Generation of layers at both sides of the inner segmentation border of the vertical cortex with a constant thickness (e.g. 0.2mm) each
2. Calculations of mean bone mineral densities (BMD) within these equidistant layers

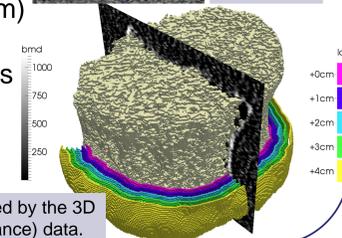This BMD(ridge distance) data is used in a forward modelling approach as outlined in the next paragraph.

Fig. 1: Total trabecular volume

Fig. 2: Layer segmentation with d=0.2mm

Fig. 3: Trabecular network (beige) covered by the 3D layers to generate mean BMD(ridge distance) data.

Deconvolution-based Forward Model

- Assuming an gaussian distribution for the MTF and accordingly for the PSF of the CT imaging system
- Deducing an edge-spread-function (ESF) and a non-infesitesimal line-spread-function (LSF)
- Putting the ESF for the spongiosa plateau and the LSF for the cortex into one function
- Setting the full mineralization to 1100mgHA/cc
- Fitting spongiosa plateau (ESF) and cortex plateau (LSF) on the BMD(ridge distance) data yields the deconvoluted cortical thickness dcCt.Th
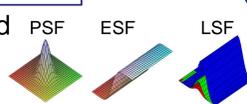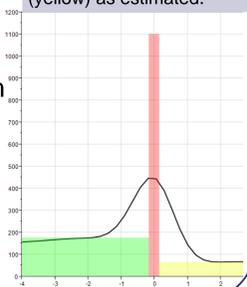- Fitting an additional epoxy plateau outside the bone (yellow) results in dcCt.Th*

This fit procedure can be done with a free δ, actually turning the cortex itself into a „test body" to access the PSF's FWHM.

Fig. 4: Forward Model with mean BMD profile (black), dcCt.Th* (red), spongiosa (green) and epoxy plateau (yellow) as estimated.

Results

The diagrams below show the BMD(ridge distance) data points and the approximation by the forward model (using the epoxy compound term) as a line for all 10 vertebrae, resulting in solutions for dcCt.Th*.
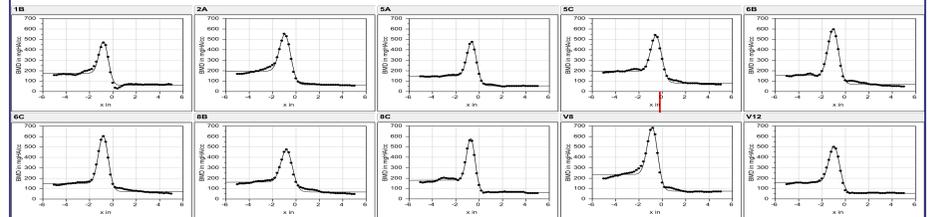

For HRpQCT scans, we find a mean cortical thickness of $(0{,}36\pm0{,}07)$ mm using Scanco Medical software (DT-Tb.Th within the cortex segmentation). Using Structual*Insight* on HRQCT data, the mean thickness of the vertical cortex segmentations is (1.52 ± 0.27)mm. Using the deconvolution-based forward modeling and assuming a mineralization of 1100mgHA/cc, a mean of (0.46 ± 0.08)mm was obtained (table 2).

| Table 2	HRpQCT	HRQCT			
	DT Ct.Th	Ct.Th	wCt.Th	dcCt.Th	dcCt.Th*
Mean Cortical Thickness in mm	0.36 ± 0.07	1.52 ± 0.27	0.52 ± 0.13	0.49 ± 0.09	0.46 ± 0.08
RMSE (HRQCT against HRpQCT) in mm		0.058	0.037	0.019	0.019
r² (HRQCT against HRpQCT)		0.38	0.75	0.93	0.93

- Graph 1 shows a weak correlation between HRQCT Ct.Th and the HRpQCT DT-Ct.Th cortical thicknesses with r²=0.38 and RMSE=0.058mm.
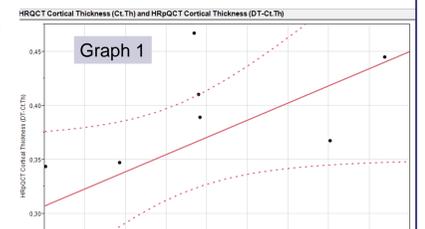
Graph 1

- This is contrasted by the strong correlation between the deconvolution-based HRQCT dcCt.Th* and the HRpQCT DT-Ct.Th (r²=0.93, RMSE=0.019mm) in graph 2.
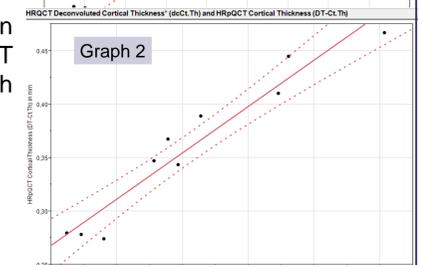
Graph 2

- Graph 3 shows the Bland-Altman plot for them, which better illustrates the residual errors with a mean offset of (0.096 ± 0.021)mm without a significant slope.

Graph 3
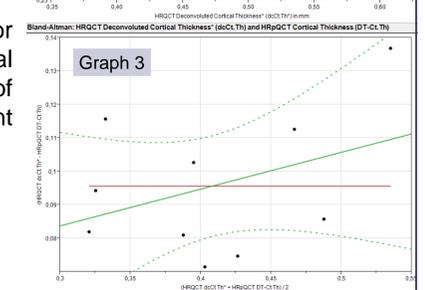
- In the 3D visualization on the right, the vertical cortex (clipped for clarification) is shown with dcCt.Th*=0.43mm from HRQCT as an example. In HRpQCT, this vertebra's DT-Ct.Th was 0.35mm.
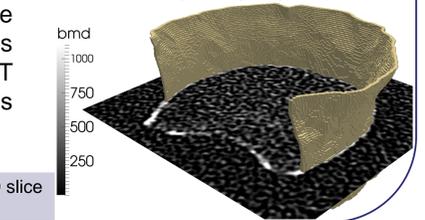

Fig. 5: Estimated cortex (clipped) over a 2D slice of BMD as assessed by HRQCT.

Conclusion

- Deconvolution-based correction reduced the accuracy error of cortical thickness (dcCt.Th*) measurements obtained on HRQCT data to 28% (compared to goldstandard HR-pQCT) whereas accuracy error of segmentation-based Ct.Th and its density-weighted refinement wCt.Th had levels of 423% and 45%, respectively.

- Using sufficient thick layers, noise is reduced and the use of the forward model in itself is another source of stability.

- The cortex can be used as a test body to estimate the scanner- and kernel-dependent point spread function.

- After semi-automatic segmentation, the determination of the deconvoluted cortical thickness runs without user interaction and, except for the mineralization, without further adjustable parameters.