Original Dan Leib 2013.
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Explanation and Recommendations for Reporting of CTParameters

25 June 2021

Recommended Set of Cortical Parameters:

(these parameters come from the UCT_LIST_MOILOG file)

- Total Area (TA)
- Bone Area (BA)
- Medullary Area (user calculated: TA-BA=MA)
- Cortical Thickness (Ct.Th: from DT-Ct.Th column)
- Polar Moment of Inertia (pMOI)
- Tissue Mineral Density (TMD: from the Mean2 column)

Recommended Set of Cancellous Parameters:

(these parameters come from the UCT_LIST_3DLOG file)

- BoneVolume (BV: from the VOX-BV column)
- Total Volume (TV: from the VOX-TV column)
- Bone Volume over Total Volume (BV/TV: from the VOX-BV/TV column)
- ConnectivityDensity (Conn.D)
- Structure Model Index (SMI: From the TRI- SMI column)
- Trabecular Number (Tb.N: from the DT-Tb.N column)
- Trabecular Thickness (Tb.Th: from the DT-Tb.Th column)
- Trabecular Separation (Tb.Sp: from the DT-Tb.Sp column)
- Volumetric Bone Mineral Density (vBMD: from the Mean1 column)

Explanation of Cortical Parameters
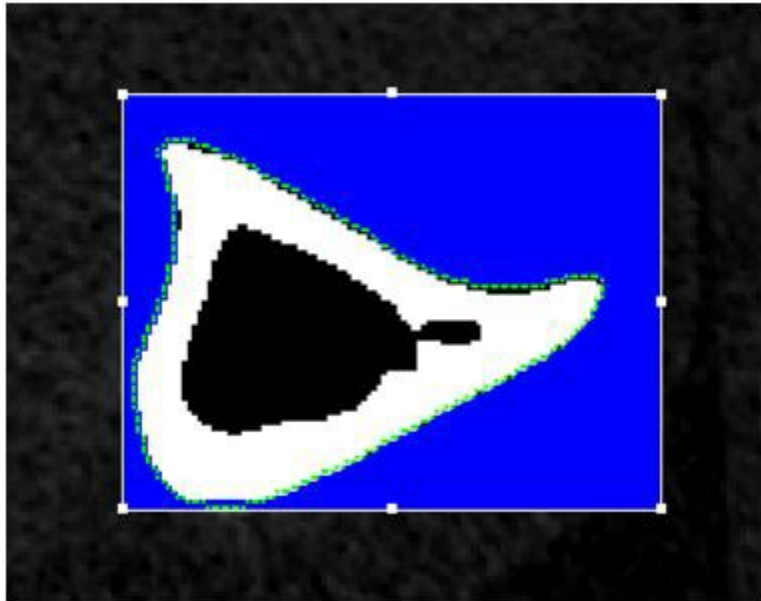
Binary
• white=bone
• black=not bone

"Bone mineral density" parameters: Any value that is calculated as "mineral per volume" in a CT scan can be considered a bone mineral density parameter and is expressed in mgHA/ccm, where HA (hydroxyapatite) is a mineral phantom. Several specific types are usually considered when evaluating bones using microct. The following are relevant for cortical bone analysis.

Parameters:

Mean2 or TMD: This represents tissue mineral density. Specifically, it is the mineral content of all of the thresholded voxels (displayed in white in the picture above) divided by the volume of all of the thresholded voxels. This is independent of the total volume of your volume of interest and reflects calculations on only what you've labeled as bone. This is typically reported for cortical bone as it represents a property that strongly contributes to a bone's overall strength. Apparent mineral density (sometimes listed as mean1) is typically not reported.

Morphology Parameters:

Parameters:

Total Area (TA): This value represents the total area, bone and medullary, contained within the contours that were drawn. It is a planar (2D) calculation expressed in mm^2. A larger total area may indicate greater resistance to fracture when bending.

Bone Area (BA): This value represents the amount of the TA which is occupied by bone, calculated from the voxels that are above the threshold value.

Medulary Area (MA): The amount of the TA not occupied by bone.

Cortical Thickness (Ct.Th): This represents the thickness of the cortical shell of bone calculated by applying the distance transformation method (sphere fitting) to the thresholded voxels. The output is an average cortical thickness that does not necessarily reflect any variation in the shell's thickness. This parameter is important as the thickness of the cortical bone strongly contributes to a bone's resistance to bending as well. See the Hildebrand papers listed below for details on the distance transformation method.

Polar Moment of Inertia (pMOI): We recommend reporting the polar moment of inertia when factors affecting resistance to bending are relevant to the research question as it is independent of the orientation of the bone in the scanner. Moments of inertia in specific directions (A-P and M-L) are sensitive to this orientation. If moments in specific directions are required for three point bending calculations, they may be calculated using a specialized set of software in the imaging lab.

Explanation of Cancellous Parameters

contour   threshold

Binary
• white=bone
• black=not bone

tissue volume (TV)   bone volume (BV)
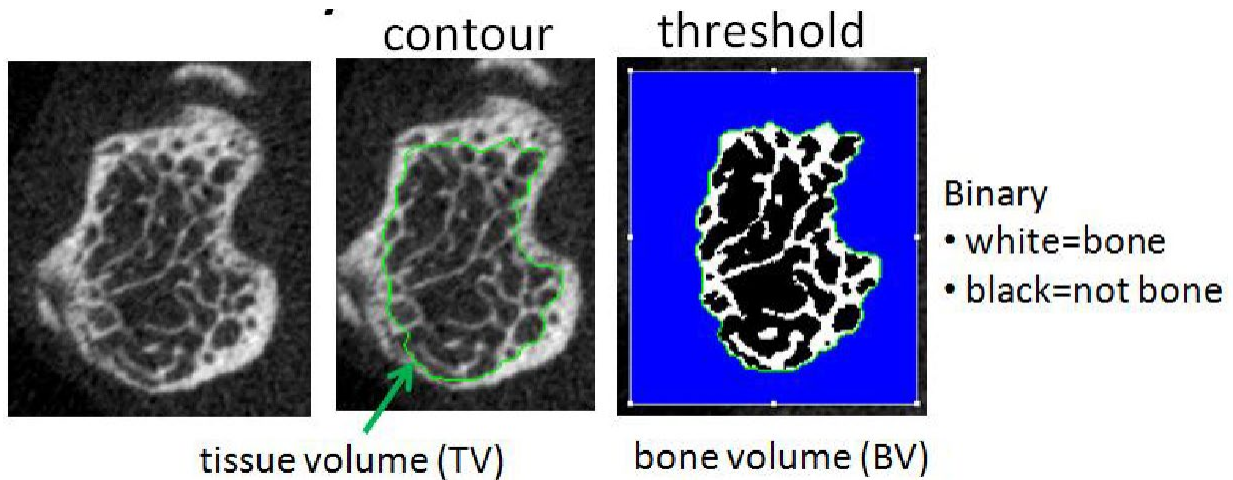
Density Parameters:

Parameters:

Mean1 or vBMD: This represents what is often called "volumetric bone mineral density," more precisely called apparent bone mineral density. Specifically, it is the total bone mineral content contained within your volume of interest divided by the total volume (TV) of your region of interest. We typically recommend reporting this value for cancellous bone as it relates directly to bone strength. It should show similar trends to BV/TV (see below). It may also be reported for the whole bone if contours are drawn around the exterior of the cortical shell.

We do **NOT** recommend reporting mean2, or tissue mineral density, for cancellous bone due to resolution/accuracy issues and to be consistent with the recommendations of Bouxsein et al. (see further reading below).

Morphology Parameters:

Parameters:

BV: A straightforward bone volume parameter based on the number of voxels captured by your thresholded value and the volume of each voxel in your volume of interest as defined by your contour.

TV: The total volume based on number and volume of voxels in your entire region of interest. Considers ALL voxels contained within your contour.

BV/TV: Bone volume fraction. This is independent of mineral density, based purely on the number of voxels that are and are not bone in your volume of interest. This parameter is generally recommended for cancellous bone analysis as it provides information on "how much" of the interior of the bone contains mineralized tissue.

The initial steps of the distance transformation method (as fully described in Hildebrand et al 1999) are performed first. Then, from the results of the initial steps:

To calculate ***Tb.Th,*** each voxel then gets the value of the radius of the maximal sphere it sits in, and twice the mean value of all structure voxels then is the mean thickness. This results in a fairly robust thickness estimation assuming adequate input data. For details on adequate data see the Notations appendix. The thickness of the trabeculae can be an indicator of their ability to participate in a bone's resistance to bending and compression.

To calculate ***Tb.Sp***, the same procedure is performed for the background of the structure, i.e. object (bone) and background (air) are switched.

To calculate ***Tb.N***, the spacing of the mid axes is calculated as for Tb.Sp. Then the inverse of the mean spacing is Tb.N.

Connectivity Density: This parameter represents one aspect of how trabeculae contribute to bone strength by estimating their interconnectivity. In short, it represents how many branches between nodes can be cut before the structure is completely separated. For a full description of how this is calculated and the theoretical underpinnings of why it is calculated that way, see Odgaard and Gundersen below.

Structure Model Index: This parameter is an estimate of the shape of trabeculae, describing the shape relative to how rod or plate –like the trabeculae are. A value of zero represents a perfect plate, while three represents a cylindrical rod. A perfect sphere would have a value of four. The geometry of trabeculae has an effect on how they behave as load bearing structures and their contribution to whole bone strength. The calculation is listed below, where BV is bone volume, dBS is the change in bone surface when the shape of the structure is dilated slightly, dr is the radius of said dilation, and BS is the bone surface area calculated through the plate fitting method:

$$SMI = 6 \bullet \frac{BV \bullet \frac{dBS}{dr}}{BS^2}$$

Further literature:

M. Bouxsein, S Boyd, B Christiansen, R. Guldberg, K. Jepsen, R Muller. Guidelines for assessment of bone microstructure in rodents using micro-computed tomography. *J Bone Miner Res* 2010;25(7):1468-86.

T. Hildebrand, P. Rüegsegger. A new method for the model independent assessment of thickness in three dimensional images. *J Microsc* 1997;185:67-75.

T. Hildebrand, A. Laib, R. Müller, J. Dequecker, P. Rüegsegger. Direct 3-D morphometric analysis of human cancellous bone: microstructural data from spine, femur, iliac crest and calcaneus. *J Bone Miner Res* 1999;14(7):1167-74.

A. Odgaard, H.J. Gundersen. Quantification of connectivity in cancellous bone, with special emphasis on 3-D reconstructions. *Bone* 1993;14(2):173-82.

Appendix

Notations:

Some of the values calculated may have marks next to them, a tilde (~) or exclamation point (!).

A tilde indicates that the value was calculated using a plate fit method, which is no longer considered to be the most valid method of calculating volumetric measurements generally speaking. For some outcome values, however, it is the only method available. These values may require conservative interpretation.

An exclamation point indicates that the calculation method requires more input data than was present and that the outcome value is probably not reliable. This is most often the case in calculation of cancellous bone morphology when trabeculae are not large or numerous enough for the numerical methods used. In some cases, such as when very young mice of certain phenotypes are scanned, this may be unavoidable. In other cases you may need to review your threshold and peel settings used when running your analysis.

Distance Transformation Method:

This method is what is used to calculate thickness, separation, and number parameters for cortical and cancellous bone. Below is a brief explanation – for a more complete explanation, see the Hildebrand papers listed above.

By distance transformation, the calculation of the metric distance of every bone (object) voxel to the nearest bone-air (background) surface is understood. These distances can be imagined as the radius of a sphere with centre in this voxel that fits inside the structure. Then redundant spheres are removed-' big sphere eats small encompassed spheres'. The result is the mid axes transformed structure with the centers of maximal spheres filling the structure completely.