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A new method of segmentation of compact-appearing, transitional and trabecular compartments and quantification of cortical porosity from high resolution peripheral quantitative computed tomographic images

R. Zebaze [a,b,*], A. Ghasem-Zadeh [a,b], A. Mbala [b], E. Seeman [a,b]

[a] Dept Endocrinology and Medicine, Austin Health, University of Melbourne, Melbourne, Australia
[b] StraxCorp PTY LTD, Melbourne, Australia

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ABSTRACT

A transitional or cortico-trabecular junctional zone exists at any location composed of both cortical and trabecular bones such as the metaphyses of tubular bones and short bones like the femoral neck. The transitional zone comprises the inner cortex adjacent to the medullary canal and trabeculae abutting against the cortex contiguous with the endocortical surface. This is a site of vigorous remodeling. Intracortical remodeling cavitates the inner cortex expanding this transitional zone at the price of compact-appearing cortex so that it contains porosity, cortical fragments that resemble trabeculae, and trabeculae abutting the eroding cortex. The porosity of the transitional zone is an important source of bone loss. It reduces bone strength exponentially and is a quantifiable `fingerprint' of structural deterioration.

A new automated method of segmentation of bone from background and bone into its compact-appearing cortex, transitional zone, and trabecular compartment is described, with a new approach to quantification of cortical porosity. Segmentation is achieved by automatically selecting attenuation profile curves perpendicular to the periosteal surface. Local bone edges are identified as the beginning and the end of the rising and falling S-shaped portions of the curve enabling the delineation of the compartments. Analyzing ~3600 consecutive overlapping profiles around the perimeter of each cross-sectional slice segments the compartments.

Porosity is quantified as the average void volume fraction of all voxels within each compartment. To assess accuracy at the distal radius and tibia, μCT images of cadaveric specimens imaged at 19 μm voxel size served as the gold standard. To assess accuracy at the proximal femur, scanning electron microscopy (SEM) images of specimens collected at 2.5 μm resolution served as the gold standard.

Agreement between HRpQCT and the gold standards for segmentation and quantification of porosity at the distal radius and tibia ranged from $R^2 = 0.87$ to 0.99, and for the proximal femur ranged from 0.93 to 0.99. The precision error in vivo for segmentation and quantification of porosity in HRpQCT images at the distal radius, given by the root mean square error of the coefficient of variation, ranged from 0.54% for porosity of the transitional zone to 3.98% for area of the compact-appearing cortex.

Segmentation of the transitional zone minimizes errors in apportioning cortical fragments and cortical porosity to the medullary compartment and so is likely to allow accurate assessment of fracture risk and the morphological effects of growth, aging, diseases and therapies.

Introduction

Eighty percent of the skeleton's mineralized bone matrix is cortical, 20% is trabecular. Of all age-related appendicular bone loss, ~70% is cortical and is the result of intracortical remodeling initiated upon Haversian canals traversing the cortex [1]. The inner cortex adjacent to the medullary canal and the trabeculae abutting against the endocortical surface form the cortico-trabecular junctional region or transitional zone [2,3].

Intracortical remodeling is particularly vigorous in this junctional region between cortical and trabecular compartments [4,5], and of all the cortical bone lost during aging, about half arises from intracortical remodeling within this narrow transitional zone [1]. The inner compact-appearing cortical region cavitates and leaves fragments, expanding the transitional zone radially at the expense of the progressively more porous, but still compact-appearing, cortex which thins from 'within' and contains more porosity [1,6].

Measurement of the morphology of the cortical bone and particularly the transitional zone is important because it is the source of

* Corresponding author at: Dept Endocrinology, level 2, Centaur Wing, Repatriation Campus, Austin Health, Heidelberg 3081, Melbourne, Victoria, Australia. Fax: +61 3 9496 3365.
E-mail address: zebaze@unimelb.edu.au (R. Zebaze).

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most bone loss [1]. The resulting porosity reduces bone strength exponentially [7], and is a quantifiable 'fingerprint' of structural deterioration which is likely to predict fracture risk and may be used as a marker of responsiveness to therapy [8]. Many methods are used to segment bone. However, none segment the transitional zone in HRpQCT images. We report an accurate and reproducible method of segmenting bone from background, segmenting bone into its compact-appearing, transitional zone, and trabecular compartments, and quantifying porosity in vivo.

Materials and methods

Segmentation of compact-appearing cortex, transitional zone, and the trabecular compartment

Ex vivo and in vivo images were processed using StrAx1.0, a custom software using a segmentation algorithm fully described in the patent [9]. Image processing begins by identifying a point 'C' within the medullary cavity which may be the centroid but this is not essential (Fig. 1). A rectangular region of interest (ROI) referred to as an 'Arm' starts at 'C' and extends to the edge of the entire image (Po). To segment, the algorithm operates from 'C'. The Arm is selected so that its length is perpendicular to the bone surface. The Arm width (AW) is selected to be narrow enough to ensure that the periosteal edge of the bone within the Arm is locally linear but contains two or more rows of voxels to avoid discontinuities due to noise or pores resulting in irregularities of bone boundaries after segmentation. $AW = R_i * \tan(\text{acos}(\Delta))$ and is automatically quantified as a function of the distance between 'C' and the nearest periosteal surface (R_i). A delta (Δ) value of 0.98 is used because it is close to 1 so that the local portion of the periosteal surface is almost linear.

The attenuation profile curve within the Arm is produced by the background, compact-appearing cortex, transitional zone and trabecular bone. At the background/bone edge, the attenuation profile curve forms an S-shape. A point P_1 is selected from which the beginning, 'K', of the sharp rise of the curve, is identified and corresponds to the beginning of the transition from background to mineralized bone (see legend of Fig. 1 for details). Point 'K' is the intersection between the circle of smallest radius originating from P_1 and the curve. The *x*,*y* coordinates (position along the Arm, attenuation) of 'K' are calculated. From 'K', a new referent P_2 is calculated from which the circle of smallest radius intersecting the curve identifies the end of the background/bone edge, 'M'; the beginning of the compact-appearing cortex. 'M' is identified after eliminating voxels between 'K' and 'M' as they may contain both the void volume of the adjacent background and the mineralized bone matrix of the cortex. Inclusion of the background void may overestimate porosity during quantification of cortical porosity (partial volume effects, see Discussion).

After finding the external bone edge within the Arm, the algorithm analyzes the inverted S shape of the remainder of the curve between P_1 and 'C' capturing the cortex, the transition from the cortex to trabecular bone, and trabecular bone in the medullary cavity (Fig. 1). The algorithm starts again from referent P_1. It first identifies the end of the sharp descent of the S curve, 'O', which corresponds to the beginning of trabecular bone. From 'O', a new referent P_3 is calculated from which 'N', end of the compact-appearing cortex and

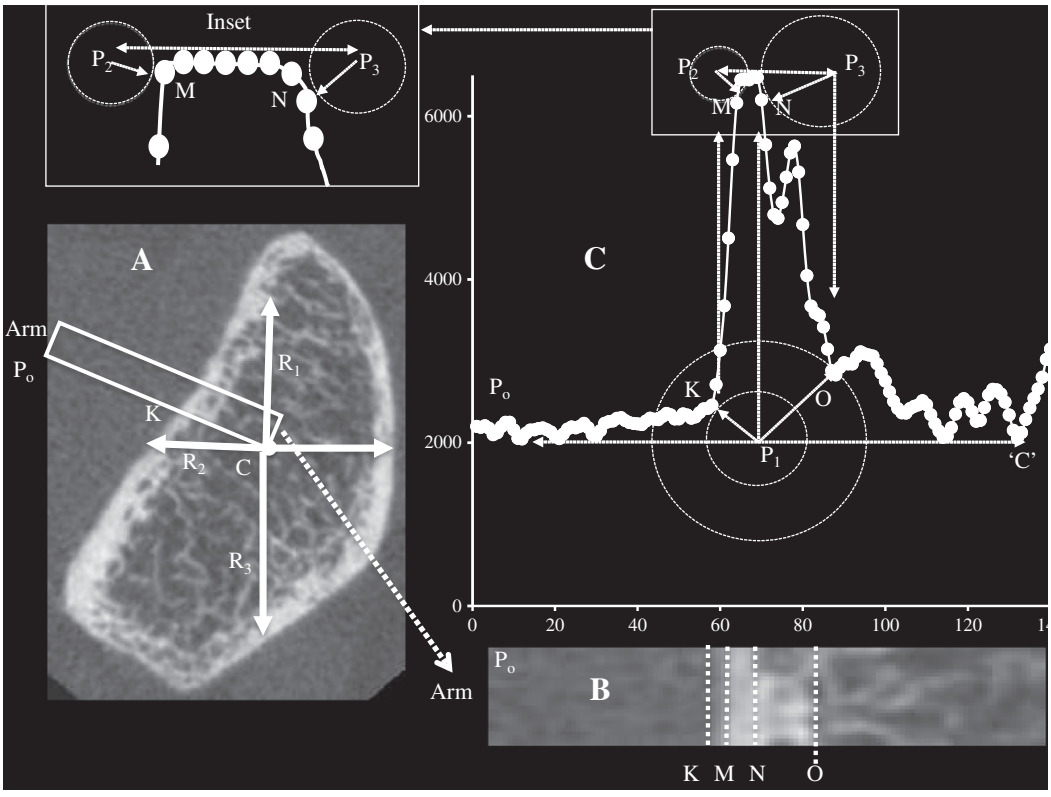

Fig. 1. (A) A gray scale image of a distal radius cross-section acquired using high resolution peripheral quantitative computed tomography. The Arm (white rectangle) originates at 'C' and extends to P_0. (B) The magnified Arm shows its contents of background, bone edges and compartments. (C) The attenuation profile. The coordinates define the bone edges and so the compartments. These coordinates are identified from moving referents. The first, P_1, has a y value equal to the background attenuation and an x value corresponding to the maximum y attenuation. From P_1, the smallest circle intersecting the attenuation profile curve is 'K', the beginning of the background/bone interface. The distance between 'C' and 'K' is the radius of the bone cross section at that angle. Radii at 12 pm, 3 pm, 6 am, and 9 am are identified by rotating 90° and applying the same algorithm. The smallest of the radii (R_i) is used to automatically quantify the width of Arm that will be used for segmentation. After identification of 'K', the moving referents P_1, P_2, and P_3 identify coordinates that define the beginning 'M' and end 'N' of compact-appearing cortex (inset). Between 'N' and 'O', the beginning of the trabecular compartment, is the transitional zone. The zone 'K' to 'M', at the background/bone interface is also a transitional zone which is excluded during segmentation to quantify porosity (see text and figure in Appendix).