Determination of the Hounsfield value for CT-based design of custom femoral stems

Arild Aamodt, Kjell A. Kvistad, Eivind Andersen, Jon Lund-Larsen, Jan Eine, Pål Benum, Otto S. Husby

From Trondheim University Hospital, Norway

CT and advanced computer-aided design techniques offer the means for designing customised femoral stems. Our aim was to determine the Hounsfield (HU) value of the bone at the corticocancellous interface, as part of the criteria for the design algorithm.

We obtained transverse CT images from eight human cadaver femora. The proximal femoral canal was rasped until contact with dense cortical bone was achieved. The femora were cut into several sections corresponding to the slice positions of the CT images. After obtaining a computerised image of the anatomical sections using a scanner, the inner cortical contour was outlined and transferred to the corresponding CT image. The pixels beneath this contour represent the CT density of the bone remaining after surgical rasping. Contours were generated automatically at nine HU levels from 300 to 1100 and the mean distance between the transferred contour and each of the HU-generated contours was computed.

The contour generated along the 600-HU pixels was closest to the inner cortical contour of the rasped femur and therefore 600 HU seem to be the CT density of the corticocancellous interface in the proximal part of cadaver femora. Generally, femoral bone with a CT density beyond 600 HU is not removable by conventional reamers. Thus, we recommend the 600 HU threshold as one of several criteria for the design of custom femoral implants from CT data.

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A. Aamodt, MD, Orthopaedic Surgeon
E. Andersen, MSc, Engineer
J. Lund-Larsen, MSc, Engineer
J. Eine, MSc, Engineer
P. Benum, MD, PhD, Professor and Chairman
O. S. Husby, MD, PhD, Orthopaedic Surgeon
Biomechanics Laboratory, Department of Orthopaedic Surgery
K. A. Kvistad, MD, Research Fellow
Department of Radiology
Trondheim University Hospital, 7006 Trondheim, Norway.

Correspondence should be sent to Dr A. Aamodt.

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Advances in radiology and in computerised design have allowed human anatomy to be reconstructed in three-dimensional (3D) geometrical and solid models. This has prompted orthopaedic surgeons and biomechanical engineers to develop customised joint implants in order to improve the fit between the prosthesis and the surrounding cortical bone. There have been several studies on the design of such customised femoral stems,¹⁻⁶ but the imaging techniques and the design criteria of the implants have differed.

Although conventional radiographs are used in the design of femoral stems, CT is currently the most accurate method for describing the anatomy of the proximal femur.⁷ On the CT image the endosteal surface appears irregular and in the proximal direction increasingly consists of cancellous bone. The CT images reflect this by depicting a transitional zone with increasing density towards the compact cortical bone. When the surgeon prepares the canal for the femoral stem, he will remove most of the cancellous bone to allow the implant to rest on bone with sufficient mechanical strength. Our aim was to assess in Hounsfield units (HU) the CT density of the inner cortical surface of the proximal femur after this bone had been removed. One HU is defined as a number on a density scale in which the X-ray absorption of water has been assigned the value of zero and the air the value of -1000.

Material and Methods

We used eight fresh-frozen human cadaver femora from individuals with a mean age of 69 years (43 to 84). The specimens appeared normal on gross inspection and on radiological examination. Two plastic rods were fixed along the femur to serve as reference markers for the orientation and scaling of the CT images and those of the anatomical slices after sectioning the specimens. The femur was embedded and fixed in an epoxy resin. After curing, one oblique and one longitudinal spur were machined into the surface of the block containing the femur. Transverse CT images (Tomoscan 60 TX; Philips, Eindhoven, The Netherlands) were obtained with a field of view of 160 mm (512 x 512 pixels) using a slice thickness of 2 mm at 10 mm increments. After CT, the femoral head was resected and all cancellous bone was removed from the proximal femur

Fig. 1

Fig. 2

Figure 1 – Anatomical section after rasping the femoral canal. The contours outline the outer cortical surface and the inner corticocancellous interface. The blue shading denotes the area not accessible to rasping. Figure 2 – CT image showing the transferred inner cortical contour (white) of the corresponding anatomical section shown in Figure 1. The HU-generated contour (green) is shown along the 600-HU pixels with distances between the contours at 100 measuring points. The blue shading denotes the area not accessible to rasping.

with curettes until close contact with the inner cortical wall was obtained and no more bone could be removed. Except for a part of the lesser trochanter, the complete inner surface of the proximal femur could be prepared in this way and the bone interface remaining after this surgical rasping was defined as ‘stabilising bone’, in that the bone on this interface was so dense that it could not be removed by conventional surgical hand tools.

Using the distance between the centres of the straight and oblique spurs on the CT images as reference, the epoxy blocks were cut into several sections corresponding to the slice positions of the CT images. Computerised images of the anatomical bone sections were obtained using a standard 300 dpi flatbed colour scanner. These were then scaled and rotated until the plastic markers fitted exactly the same markers on the corresponding CT image. Further controls of image congruence were made by comparing the outer cortical contours of the scanned image of the specimen with the CT image. With the two images superimposed exactly, a contour curve was interactively generated along the prepared inner cortical wall (Fig. 1). The contour was then transferred to the CT image, outlining the interface between the removable cancellous bone and ‘stabilising’ cortical bone. Thus, the HU value of the pixels beneath the contour reflected the density threshold of the bone not accessible to further manual rasping (Fig. 2). To investigate the HU value to which this contour was closest, we generated on the CT image HU-based contours following pixels with HU values at nine intervals from 300 to 1100 HU. The distance between the inner cortical contour and each of the HU-generated contours was measured at 100 evenly distributed points (Fig. 2). The HU-generated contour closest to the inner cortical contour on the image of the scanned

specimen was regarded as representative of the CT density of ‘stabilising’ bone. An algorithm was written and implemented into our graphics software (Medivision; Scandinavian Customized Prosthesis Inc, Trondheim, Norway) to perform these computations automatically.

Areas of the slices to be included in the analysis had to fulfil the following criteria:

- 1) The cut surface of the anatomical section had to originate from the same position as the centre of the corresponding CT slice. This was checked in two ways. The distance between the longitudinal and oblique spurs had to be identical on the anatomical slice and the CT image, and, after identical scaling and rotation of the slices, the outer contours of the two images had to be congruent.

- 2) Each 100-HU interval from 300 to 1100 HU had to be represented by pixels along at least 50% of the endosteal circumference of the CT slices. Following this, the metaphysis extending down to 20 to 30 mm distal to the lesser trochanter was the main area of interest. Distal to this level there was more abrupt transition from low-density bone marrow to high-density cortical bone.

- 3) Areas to be examined had to be accessible to manual rasping, which only excluded a part of the lesser trochanter. They could easily be identified on the images of the scanned anatomical sections (Fig. 1).

- 4) The contours following the pixels of each of the nine HU levels on the inner cortical surface were generated automatically. In some areas of cortical density below 1100 HU, the HU-based contour transversed the cortex to the periosteal surface. Therefore, areas in which the automatically-generated contour at 1100 HU did not follow the inner cortical surface were excluded from further analysis. Altogether, the measurements originated from 4383 points in 55 sections from eight specimens.

The beam-hardening effect of the epoxy resin surrounding the femur was studied in one specimen, which was not one of those needed in the original study. A steel ball with a diameter of 1 mm was placed in the femoral cortex, serving as a reference marker during the CT scanning. Transverse CT images were then obtained using the same scanner and the parameters previously described. Thereafter, the specimen was embedded in epoxy resin and, after curing, a new series of transverse CT images was obtained while keeping the femur in exactly the same position in the gantry as during the index scanning. Automatic contours along the 600-HU pixels were generated and the congruence of the curves was measured.

The results are presented as mean values of the distance between the inner cortical contour of the scanned specimen and each of the HU-generated contours. The 95% confidence interval (CI) for the mean value is given. We used a one-way ANOVA test for statistical analysis.

Results

The HU-based contour generated along the 600-HU pixels was closest to the contour along the interface remaining after rasping of the proximal femur (Fig. 3). The mean distance between this inner cortical contour and the 600-HU contour was 0.027 mm (SD 0.52, range -3.56 to +5.75). Contours generated along pixels with lower CT density appeared inside the rasped interface contour, whereas those based on higher HU values were outside this. There was a statistically significant difference between the mean distance from the 600-HU contour to each of the other HU-generated contours ($p < 0.001$). In this experiment automatic contours were generated at every hundredth HU from 300 HU to 1100 HU, but it is possible to compute an HU value by which the distance to the anatomical inner cortical contour is minimised. This was at 580 HU (Fig. 3).

We also examined whether the contour of the inner cortical surface followed closest to the 600-HU contour at all levels of the proximal femur. The tip of the lesser trochanter was defined as the border between the metaphyseal and the diaphyseal part of the upper femur. As seen in Figure 4, in both regions the inner cortical surface of the rasped femur is closest to the 600-HU contour on the corresponding CT images. As would be expected, the transition zone of bone with density from 300 to 1100 HU is much wider proximally than distally. The mean thickness of these zones in the areas investigated is 1.87 mm and 0.97 mm, respectively.

Figure 5 shows the distance from the anatomical inner cortical contour to the automatically generated contour along the 600-HU pixels in each of the specimens. Statistically, there was a significant difference ($p < 0.01$) between the specimens. The average deviation between the contours, however, was at a maximum of 0.18 mm.

Comparison of the 600-HU contours in one femur before and after embedding the specimen in the epoxy resin showed that the radius of the curve appeared to be smaller by 0.19 mm after adding the epoxy. This implies that the epoxy alters the density scale of the CT images, a phenomenon which may be attributed to the beam-hardening effect of the material surrounding the femur.

Discussion

The design of customised femoral stems requires definition of the endosteal cavity in which the implant is to fit exactly. Several other factors, however, have to be taken into consideration when determining the design. The stem must be insertable through an opening at the calcar after resection of the neck. The complex geometry and widening of the canal in the trochanteric region will prevent a 100% fill of the femoral canal. Areas for priority contact with the inner cortex may be assigned in order to achieve a close-to-

Fig. 3

The mean distance from the anatomical inner cortical contour after rasping to each of the HU-generated contours. The negative figures on the Y-axis indicate that the HU-generated contour is inside the inner cortical contour. Error bars indicate the 95% confidence interval.

Fig. 4

The mean distance from the anatomical inner cortical contour to each of the HU-generated contours on the CT image in the proximal and distal regions. The negative figures on the Y-axis mean that the HU-generated contour is inside the inner cortical contour. Error bars indicate the 95% confidence interval.

Fig. 5

The mean distance from the anatomical inner cortical contour to the 600 HU contour in each of the eight specimens. The negative figures on the Y-axis mean that the HU-generated contour is inside the inner cortical contour. The specimens were not examined in the same order as appearing on this graph. Error bars indicate the 95% confidence interval.

normal transfer of stress to the proximal femur. The prosthesis must be fitted into a bed of dense, cortical bone, which can provide optimal mechanical stability to the prosthesis,¹ without the endosteal cavity containing the implant extending into cortical bone. This could possibly endanger the femur during reaming, weaken the femoral cortex and create non-physiological transfer of stress to the bone.¹

During design closed contours are generated along the periosteal and endosteal surfaces of the femur. Two requirements have to be fulfilled; the contour has to reflect the true dimensions of the object to be delineated and it must identify the layer of the endosteum in contact with the femoral stem. The contours can be drawn manually on the CT images, but contour-detecting algorithms are usually written to standardise and automate the design process.^{4,8} One method of identifying the corticocancellous interface is by using absolute thresholding, and to achieve this Hounsfield values between 500 and 800 have been cho-

sen.^{2,4} Garg et al² found that a downscaling of the contour following the corticocancellous interface by 1 mm is represented by cancellous bone with a CT density of 275 HU. This is in agreement with our measurements in the metaphysis showing the mean distance between the 300 and 600 HU contours to be 1.1 mm. Distal to the lesser trochanter this distance was only 0.4 mm. Contours based on specific HU values, however, may traverse the cortex in regions with low cortical density rather than describing closed contours along the endosteal surface, partly necessitating a manual generation of contours.

Rothuizen et al⁸ described a method of relative thresholding in which the selection of a contour point is based on a percentage of the total attenuation distance between the maximum and minimum density values in the cross-sectional CT image of the bone. They found that by using the relative density, rather than a specific HU value, the contours describing the outer and inner surfaces of the cortex deviated less from the true anatomical dimensions.

Reuben et al⁴ used a similar contouring algorithm. First, they generated an outer cortical contour based on a bone-density gradient, and then applied a dynamic density-threshold technique to detect the pixels representing the inner cortical contour.

Our aim was to define the HU value of the bone in the proximal femur accessible to manual removal with conventional surgical hand tools or, in anatomical terms, the corticocancellous interface. According to our results the stabilising bone of the endosteal cavity has a CT density of approximately 600 HU in both the metaphyseal and diaphyseal regions. In a similar study with standard reaming techniques, Hua, Mai and Walker⁹ found that 300 HU represented the density of the bone at the remaining surface of the femoral cavity.⁹ They also rasped the femoral canals until contact with hard bone was achieved and there is no obvious explanation as to why their results differ from ours.

There is, however, a small variation in the CT density of this interface in the eight specimens included in our study. The maximum deviation between the 600-HU contour and that generated along the rasped interface was 0.18 mm. Due to this variation, and the potential dimensional inaccuracies of the CT image, we have implemented a downscaling of 0.5 mm in radius in the design algorithm of the customised femoral stem compared with the boundaries created by the 600-HU contour.

In an experimental study of human cadaver femora, Rubin et al⁷ found a mean inaccuracy of 0.8 mm (sd 0.4) on two-dimensional measurements on CT images compared with the true anatomical dimensions. As a result of their study, the radius of a customised femoral stem should be downsized at least 0.8 mm from the 600-HU contour in order to be insertable safely. The resulting dimensional inaccuracies, however, differ from one CT machine to another.

In a clinical situation, the cancellous bone in the metaphysis of the femur is compressed against the endosteal cortex, rather than being removed, during the final rasping of the femoral canal before the stem is inserted. Because of this the use of the 600-HU criterion for defining the geometry of the prosthesis will necessarily lead to a femoral implant which is too large.

In our study the CT images were obtained from femora embedded in an epoxy resin. Like the soft tissues in a clinical situation, the epoxy resin will contribute to a beam-hardening effect, which can alter the density scale of the CT image of the femur. In a separate study, we performed CT on one femur before and after embedding the specimen in epoxy resin. Adding the epoxy resulted in the mean

radius of the femoral canal appearing to be smaller by 0.19 mm than without the resin. In a previous study, we have shown that the radius of the proximal femoral canal on the CT image appeared on average to be larger by 0.23 mm after removal of the soft tissues around the femur.¹⁰ Thus, the attenuation of the CT density induced by the epoxy is comparable to the beam-hardening effect of the soft tissues. These studies indicate that a CT density of approximately 600 HU in a clinical situation represents the corticocancellous interface.

Although the corticocancellous interface of the proximal femur is not well demarcated anatomically, we conclude that a density of 600 HU on CT images obtained under experimental conditions will represent this surface. Bone with higher density is generally not removable using conventional surgical hand tools. The 600-HU contour can be used as a guideline in the design of customised femoral implants, but dimensional inaccuracies in the CT data must be taken into account.

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