Mathematical Morphology Based Volumetric Analysis of Bone Density Around Implant in Post-Operational Follow-up of Per-Trochanteric Fractures

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Abstract: Per trochanteric fractures are common in an ageing population with osteoporosis and account for about half of all hip fractures. Treatment of per trochanteric fractures with extramedullary or intramedullary implants is challenging especially in unstable fractures. In order to improve the mechanical anchorage of the screw and prevent re-operations, various attempts have been made to reinforce the fragile bone with polymer based injectable materials. However, volumetric control of delivered material and/or measurement of bone density in post-operative follow-up remains challenging. This study presents the basic principles of a new algorithm for CT based volumetric analysis of the bone density in the region adjacent to the implant in the femoral head in comparison to the non-operated hip. The method was also used to track long term bone density changes at 3 to 6 months of follow up.

1 INTRODUCTION

Per trochanteric fractures are common in elderly, and account for about half of all hip fractures (Hermann et al. 2012). Treatment of per trochanteric fractures with extramedullary or intramedullary implants is challenging because of poor bone quality, which eventually leads to reoperations in up to 5% of the cases mainly in unstable fractures. Special mechanical solutions are proposed to cope with the problem of implant anchorage (Aros et al. 2008). In order to improve the mechanical anchorage of the screw and prevent re-operations, various attempts have been made to reinforce the fragile bone with polymer based injectable materials, such as poly methyl methacrylate (PMMA) (Stoffel et al., 2008; Gupta et al., 2012) or Calcium phosphate (CaP) (Mattsson and Larsson, 2004; Fuchs et al., 2019). Bioresorbable calcium sulphate/hydroxyapatite (CaS/HA) is reported as a promising solution of implant anchoring problem. The compressive strength of the material is higher than the cancellous

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bone (Nilsson et al., 2003). A recent study (Kok et al., 2021) has verified that the CaS/HA material spreads in the trabecular structures and protects the bone from fracturing at low loads compared to control trabecular bone. Special procedures during per trochanteric fracture surgery and control of the delivery of CaS/HA at the interface of lag-screw and osteoporotic bone can enhance the immediate anchorage (Raina et al. 2022). The biological anchorage can be further increased by systemically administering zoledronic acid (ZA), a bisphosphonate that seeks the HA material placed around the implant and induces cancellous bone regeneration. However, precise volumetric control of material delivery and/or bone density in post operational follow-up remains challenging. Areal bone mineral density obtained from dual energy X-ray absorptiometry (DEXA), currently used in osteoporosis diagnostics, could now be outperformed by volumetric bone mineral density estimated by peripheral quantitative computed tomography (pQCT) (Watcher et al. 2001). In case of per trochanteric fractures treatment with implants, pQCT could be used for both: volumetric control of material delivery and measurement of longitudinal bone density changes. Volumetric representation and precise delineation of volume of interest surrounding the implant in bone allows the follow up of bone density and implant anchoring during the whole treatment process.

The aim of this study was to elaborate a volumetric analysis of region surrounding the implant in femur and algorithms for evaluation of bone density changes over time and in regard to non-operated areas.

2 METHODS

Trochanteric fracture patients undergoing internal fixation with a dynamic hip screw (DHS) system were included in the study at the department of Orthopaedics and Traumatology, Lithuanian University of Health Sciences. The study was ethically approved by the hospital ethics board (P1 BE-2-76/2019). In the control group, all patients were treated per standard care guidelines and were given a systemic infusion of zoledronic acid, 1-2 weeks post-surgery. The experimental arm consisted of DHS augmented with a CaS/HA biomaterial followed by systemic ZA administration. A volumetric imaging of pelvic region of 9 patients (3: control, 6: treatment) was performed by applying a GE Revolution™ Discovery™ HD CT machine (GE Healthcare, Waukesha, WI). Slice thickness was 0,625 mm, matrix of 512*512, postprocessing was not applied, each voxel was representing 0.70312 x 0.70312 x 0.625 mm of space. The intensity of images was 256 levels resolution represented in Hounsfield units.

Points of metal implant had a few fold higher intensities over the rest of points representing bone or muscle tissues. Therefore, they were forming an easy delineable reference object for determination of volume of interest. Actual volume of interest – implant surrounding environment – was determined using 3D mathematical morphology procedure "dilation" (MatLab function "*imdilate*", using "*sphere*" structural element):

$$A \otimes B = \left\{ z \middle| \left(\hat{B}\right)_z \cap \neq \emptyset \right\}, \tag{1}$$

while $\hat{B}$ is the reflection of the structuring element B. In other words, it is the set of pixel locations z, where the reflected structuring element overlaps with foreground pixels in A when translated to z. The procedure selects points surrounding the reference object. We used 7-point radius structural element to select whole volume of interest, excluding the closest space to the implant selected by 1-point radius structural element. The final volume of interest was 14-voxel-thick environment surrounding the implant and excluding 2-voxel-thick closest points to the metal implant. Considering the voxels' size, it roughly could be estimated as 10 mm – thick environment around the metal. Such volume of interest was accepted by experts as most suitable for implant anchoring and bone density investigations. Determined volume of interest was transformed into point cloud representation, where every point at certain coordinates was carrying information about original intensity of CT-scan representation in Hounsfield units.

Reference volume of interest was taken from the counterpart volume on the other side of the body – non-operated femur. As far the anatomical pelvis-femur structures on the left and the right side are almost symmetric, we identified the vertical axis of symmetry of pelvis and aligned flipped point cloud representation of operated pelvis-femur side to the non-operated one. For this procedure we used sparse point cloud representation of the structures only by selected key-points, having empirically selected intensity of 470 - 480 Hounsfield units. It resulted in representation of bone structures by roughly 50000 points instead of 13000000 original representation points. The validity of representation was visually controlled by the experts. Such reduction in representation allowed stable and comparatively quick operation of point cloud alignment procedures (Matlab functions "*pcregistericp*"; "*pctransform*") and gave visually confirmed good result. The obtained point cloud transformation matrix was used to transform coordinates of point cloud, representing determined implant surrounding environment, to obtain image intensities in reference region of interest on the unoperated side. The described procedure allowed to compare the bone density around the implant to the unoperated reference side. Graphical representation in form of point cloud of the differences can reveal detailed changes in bone density.

Long term follow-up of the bone density changes around the implant was based on the same principle of spatial alignment by sparse representations of the bone structures. At this time, compared CT volumetric representations were taken in 3- or 6-months interval, so, spatial point cloud representations of compared structures eventually can have certain geometrical differences. Therefore, we estimated differences in points of compared clouds, which were pairwise closest to each other by Euclidean distance in space. Pairs of such closest points in compared point clouds were found using the Kd-tree based search algorithm (Muja et al. 2009) (MatLab function "*findNearestNeighbors*").

3 RESULTS

Process of volume of interest determination in CT scan volumetric lower body representation is illustrated in Figure 1 by typical real clinical image. The key-points selected for sparse spatial representation of left and right parts of pelvis area are marked by "o" and "+" respectively. Implant, as solid body, is shown in black. Implant surrounding environment is shown in blue.

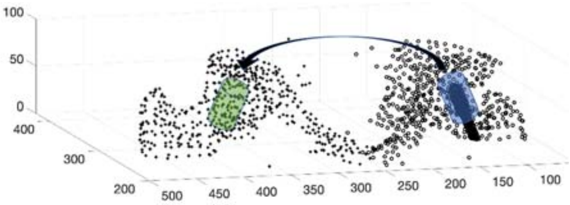

Figure 1: Sparse representation of left and right pelvis for determination of region of interest surrounding the implant (blue cylinder body) and its counterpart on the opposite side (green cylinder body). The number of points representing structure of pelvis here is reduced for visual clarity.

After determination of implant surrounding environment, the sparsely represented spatial structure (marked by "o") is flipped and aligned to its counterpart on the other side (marked by "+"). The corresponding volume in the unoperated side is marked in green as control volume of interest. The whole procedure can be visually controlled.

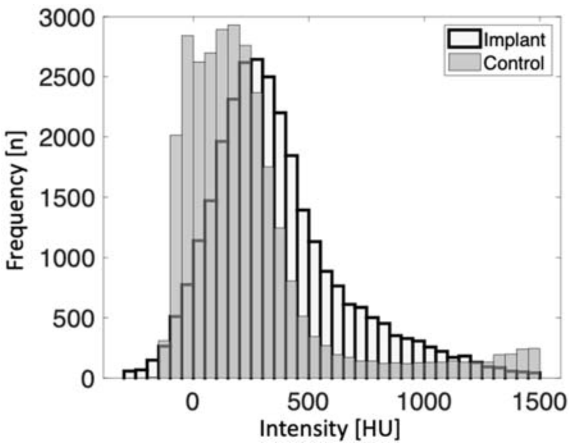

Figure 2: Histograms of intensity values of implant surrounding environment together with counterpart environment from unoperated side.

Histogram of intensity values of implant and the surrounding cancellous bone compared with the unoperated side is presented in Figure 2. As one can notice, bone density adjacent to implant is significantly higher than in control volume from the unoperated side. Detail spatial distribution of differences across the whole volume of interest is obtained by 3-D presentation of points in actual space positions where differences are represented by colour and marker size. Such representation is illustrated in Figure 3 and revealed a noticeably bigger differences are situated close to the implant surface in patient where CaS/HA filling was used to enhance anchorage of the implant (see right side of the graph). There is no such clearly visible difference in case when CaS/HA filling was not used.

Histograms of bone density differences in cases illustrated in Figure 3 are presented in Figure 4. This is preliminary, yet promising result, showing the increased bone density when CaS/HA filling was used.

Example of investigation results of long-term changes in bone density during three months follow-up is shown as histograms of spatial points intensity in implant surrounding environment immediately after operation and after three months (Figure 5).

Slightly visible difference in histogram supplemented by spatial representation of pairwise comparison of intensities in each point of point cloud of implant surrounding environment gives much more detailed diagnostic information (Figure 6).

Most visible positive changes in bone density after three months are in the implant surrounding area, at the tip of the implant. It is a promising result showing that bone density increased at the region where most of CaS/HA filling was delivered.

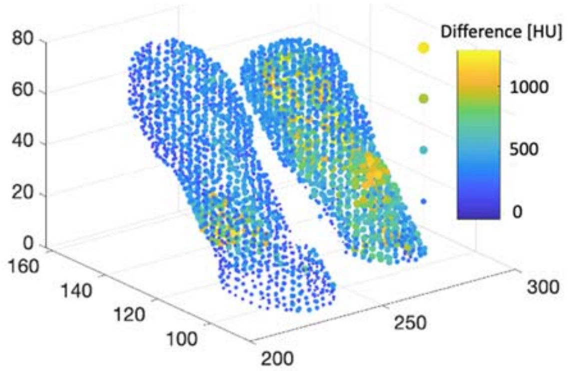

Figure 3: 3-D presentation of points of implant surrounding environment in actual space positions in the patient when CaS/HA filling was used (right side) and in the contralateral side of the same patient where no filling was used (left side). The differences between intensity of implant surrounding environment and counterpart unoperated side are represented by colour and marker size as indicated on the right side of the graph.

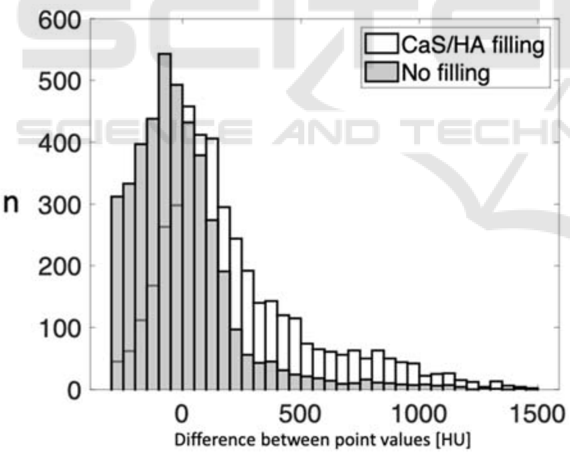

Figure 4: Histograms of bone density differences in case when CaS/HA filling was used compared with un-augmented controls. The data are from cases illustrated in Figure 3.

4 DISCUSSION

Dual energy X-ray absorptiometry (DEXA), routinely used for evaluation of bone mineral density in osteoporosis diagnostics gives Ca concentrations estimates in absolute values. However, the region of interest for estimates could not be defined so precisely as we show for CT-scan volumetric images. Usage of calibrating technics, as in peripheral quantitative computed tomography, could offer acceptable precision for Ca concentration estimation.

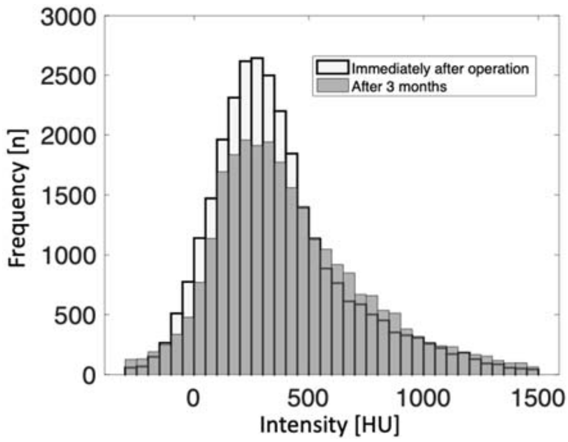

Figure 5: Histograms of intensity values of implant surrounding environment immediately after operation and after 3 months.

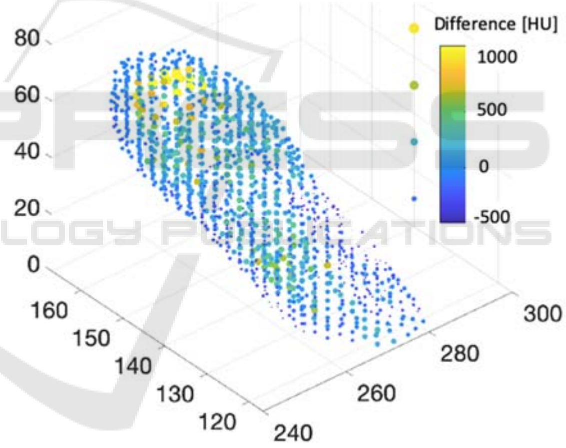

Figure 6: 3-D presentation of differences between intensity of implant surrounding environment immediately after operation and after three months.

On the other hand, we are mostly interested in changes of Ca concentration than absolute values during post operational follow up, therefore CT-scan volumetric imaging supplemented with algorithms of precise determination of volumes of interest, as we present here, could outperform DEXA in diagnostic value.

The presentation of volume of interest as point cloud gives us the new possibilities of facile data management and evaluation using comparatively small computational resources. Methods of spatial transform and alignment allow to perform detailed comparison of intensity in every particular spatial point of real investigated object. Point-to-point comparison of intensities revealed detail dynamics in bone density caused by implant insertion and special chemical means to reinforce implant anchorage. Detail 3D representation of differences in bone density gives us a visual control for selection of difference estimates to be used for evaluation of effect of chemical reinforcement materials used. In this study we have very limited amount of patient data and we show only preliminary results. However, the aim of this study was to show the technical means to be used in such studies and to reveal the directions of further development.

One of the challenging tasks revealed in this process was determination of volume of interest in the particular anatomical structures (counterpart volume of interest in the unoperated side) – determination of reference points. In this work we selected the points in the lower body CT scan according the intensity, which was empirically selected by visual control. The expert was aiming to have as much as possible area of pelvis to be represented with minimal number of points. After several attempts we ended up with roughly 50000 points selected out of 13000000 original representation points. Changing the number of selected points even by 2-folds up or down from the used one did not have any significant impact on accuracy of spatial representation and subsequent alignment procedures. Nevertheless, additional investigation of optimal number of points and methods of their selection is needed. We simply selected the existing original points of volume representation, but construction of new reference points in regard to local geometric properties of special anatomic structures would be a promising direction of investigations.

5 CONCLUSION

Point cloud presentation of objects or volumes of interest in volumetric CT-scan data reveals the new possibilities of facile data management and evaluation using comparatively small computational resources at the same time giving the valuable diagnostic results.

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