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Preliminary study of bipolar hip prosthesis – influence of acetabular bone interactions on bone morphology

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Abstract

Periprosthetic bone changes following hip arthroplasty are yet to be completely described. The material consisted of imagistic records (X-ray films, CT and MRI scans) and of acetabular bone tissue sampled from 14 cases with femoral head prosthesis and revision of the prosthesis fixed and decalcified in Duboscq–Brazil solution and stained with Hematoxylin and Eosin, trichrome van Gieson and trichrome Masson. Acetabular bone is home of a great variety of morphological changes that can be divided in degenerative and regenerative changes seen in both compact and trabecular components but only inside the maximal pressure area of the acetabular roof. Our preliminary morphological study revealed the existence of an adaptation effort to the mechanical stress materialized through a dynamic process of bone remodeling in the maximal pressure area.

Keywords: hip prosthesis, acetabular bone, morphology, remodeling.

Introduction

The stress reaction begins when an abnormal quantity of stress is released on a bone without being followed by a resting period, which may allow adapting responses. This can be shown through the imaging techniques, like an area of bone remodeling before any fracture occurs, in which the bone is weakened but not yet broken (there is no evidence of a fracture line) [1, 2]. The changes in periprosthetic bone density after hip arthroplasty are not well detailed in the literature. Little is yet known about the bone-remodeling phenomenon of the acetabulum after the insertion of the prosthesis, a phenomenon that can be considered a protecting reaction against the stress, which occurs behind the acetabulum [3].

The aim of this study is a preliminary morphological evaluation of bone changes in the acetabular areas of maximum pressure, which were identified with the help of an experimental design based on the finite elements method in a previous study [4].

Materials and Methods

The initial group of patients selected for this study included 1007 patients admitted in the Department of Orthopedics of the Emergency County Hospital of Craiova between 2003 and 2007, who underwent different procedures for hip prosthesis, named **Group I**.

From this initial group 14 cases with hip prosthesis readmitted for prosthesis revision were selected, which represented our study group, named **Group II**.

We also designed a group of seven cases with ages between 60 and 71-year-old, without femoral head fracture, admitted in the Department of Radiology of the same hospital for other complaints, that underwent imagistic evaluations – Magnetic Resonance Investigation (MRI) and Computed Tomography (CT) of the acetabular area, as control group for imagistic investigation, named **Group III**.

The algorithm of investigation included:

- Evaluation of the main clinical data;
- Imagistic study;
- Histopathological study.

Studied material

The studied material was provided by the following data sources:

- For the clinical study – medical charts of patients included in Groups I and II;
- For the imagistic study – X-ray films of patients included in Group II obtained both before and after the prosthesis revision and CT and MRI scans of patients included in Group III;
- For the histopathological study – bone tissue fragments from Group II cases, sampled from the acetabular area that was in contact with the prosthetic components,

exposed to the highest mechanical forces, as indicated by the experimental model, and from normal neighboring areas.

Methods

Databases were created and al parameters taken into consideration were included.

Clinical study

The parameters taken into consideration were:

- Epidemiologic parameters: gender and age;
- Clinical parameters: site of femoral head lesion, type of initial prosthesis, type of revision prosthesis.

Imagistic study

The equipment used for imagistic investigation was:

- Classic radiology equipment, KRISTAL model 90/20 (Producer DMS APELEM, France);
- Spiral AURA PHILIPS CT scanner with one spiral and 3D reconstruction;
- MRI equipment, GE SIGNA 1 T with the following examination sequences: Cor T1, Cor T2, Cor STIR and Ax T2.

The imagistic evaluation followed the algorithm:

- X-ray examination in dorsal decubitus, anteroposterior incidence;
- MRI of pelvis in two steps: (1) Cor T1/T2/STIR sequences and (2) Ax T1/T2/STIR sequences;
- CT of pelvis 5/5 with 3D reconstruction of the hip area.

Histopathological study

The tissue samples for the microscopic evaluation were taken and processed from the cases in Group II.

The identification of the acetabular bone areas needed for sampling was performed using an experimental model for bone stress evaluation with the help of the finite elements method, these results being published before [1]. We must remind, from our previous study, that in bipedal support, the area of maximal pressure on the acetabular bone looks like a narrow strip near the anteroposterior acetabular ridge with values decreasing from the posterior to the anterior aspect (Figures 1 and 2). In monopod support, the area of maximum pressure exerted on the acetabular bone increases, becomes oval, with a maximal diameter in sagittal plane and orientated towards the anterior part of the superior acetabular wall. The pressure values have a decreasing trend from the lateral to the medial aspect (Figures 3 and 4).

Bone tissue fragments were sampled, where possible, during prosthesis revision, according to the following algorithm:

- one fragment from the center of the acetabular area of maximum pressure, medial from the acetabular rim;
- one fragment from 1 cm towards the medial aspect, outside the maximum pressure area of the acetabulum;
- one fragment from 1 cm towards the posterior aspect, outside the maximum pressure area of the acetabulum;
- one fragment from 1 cm towards the anterior aspect, outside the maximum pressure area of the acetabulum.

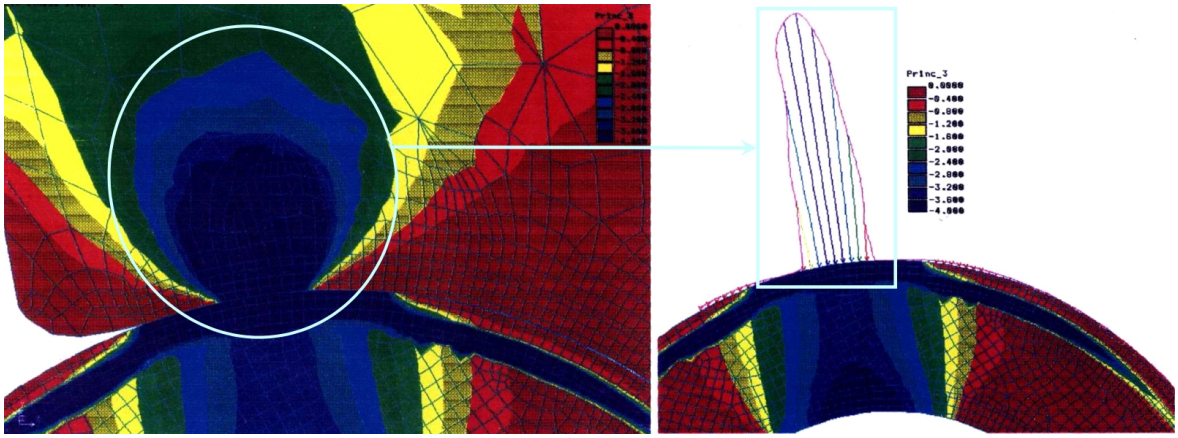


Figure 1 – ***Pressure area on the acetabular bone in bipedal support – frontal view.***

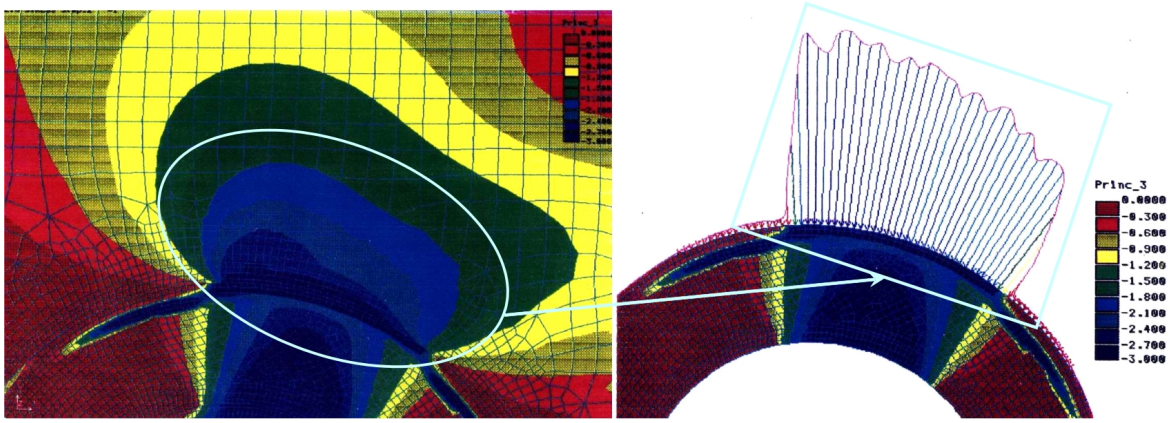


Figure 2 – ***Pressure area on the acetabular bone in bipedal support – sagittal view.***

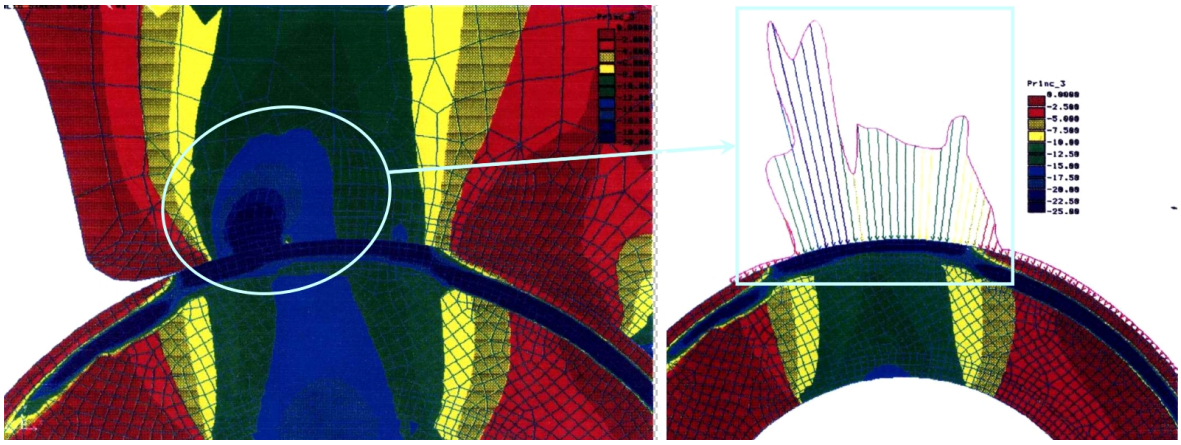


Figure 3 – ***Pressure area on the acetabular bone in monopod support – frontal view.***

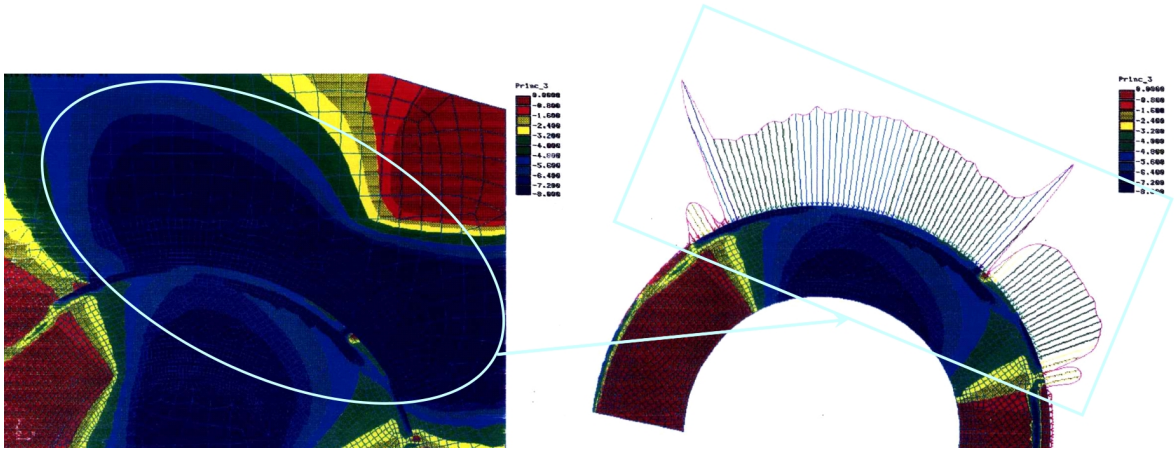


Figure 4 – ***Pressure area on the acetabular bone in monopod support – sagittal view.***

The sampling algorithm was designed in order to obtain tissue fragments from both compact and trabecular areas.

Tissue fragments were fixed and decalcified in Duboscq–Brazil solution, embedded in paraffin and the 4 µm sections were stained with Hematoxylin and Eosin, and special stains for connective tissue – trichrome van Gieson and trichrome Masson – and immunomarked for two types of collagen fibers. For immunomarking, ABC method was used after initial pretreatment with pepsin. The antibodies used are listed in Table 1.

Table 1 – ***Antibodies used in the study***

Antibody	Source	Dilution
Collagen type I (COL-1)	Santa Cruz Code sc-59772	1:50
Collagen type II (003-02)	Santa Cruz Code sc-59958	1:50

The morphological aspects taken into consideration were:

▪ Changes in the cell population of the acetabular bone roof, which were assessed both qualitatively and quantitatively in:

– contact area;

– compact bone tissue;

– trabecular bone tissue.

▪ Changes in the acetabular bone matrix.

The histopathological aspects were selected using an Olympus CX31 microscope with the ×4 eye-piece and the ×4, ×10, ×20 and ×40 Plan Apo objectives.

The most significant images were acquired using an Olympus DP12 digital camera and the AnalySIS Pro 3.2 software. The microscopic images were analyzed and the morphometric evaluation was accomplished also using the AnalySIS Pro 3.2 software, after previous calibration.

Radiographic records were scanned with an AGFA SNAPSCAN 1236 scanner.

For the morphometric assessment of the cell population the next algorithm was used:

▪ For each case: five fields were randomly selected, with the ×40 objective on HE stained slides;

▪ For each field cellular density, expressed in cells/mm^2, was determined, using the formula:

$$\frac{\text{No. of cells (osteocytes)} \times 1000}{\text{Field area [µm]}}$$

and assigned the symbols: OcD1, … to OcD5.

▪ For each case, mean cellular density – MOsD, expressed in cells/mm^2 was determined, using the formula:

$$\frac{\text{Doc1} + \text{Doc2} + \text{Doc3} + \text{Doc4} + \text{Doc5}}{5}$$

▪ For each type of area, maximal value (MAX), minimal value (MIN), average and standard deviation (STDEV) for cellular density were calculated.

The field area for the ×40 objective was **20846.9 µm^2**.

All data obtained from the three studies were processed and statistically analyzed the Microsoft

Excel, module from the Microsoft Office 2003 Professional software package.

Results

Clinical study

Type of intervention

We sorted the cases using two criteria. The first one was the temporal type of intervention according to which two categories were defined: primary intervention and revision. From the total number of 1007 interventions, the revisions represented 1.4% (Figure 5).

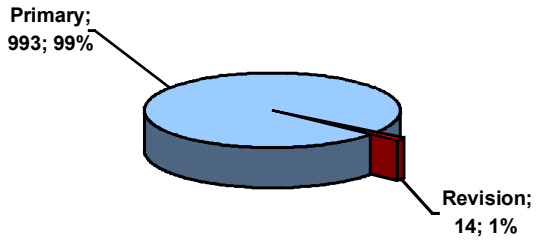


Figure 5 – ***Frequency of revisions in studied group.***

The second criterion was the type of arthroplasty according to which three categories were defined: partial prosthesis, total prosthesis and bipolar prosthesis.

In Group I, the majority of arthroplasties were the partial ones, followed by prostheses. The distribution and frequency was the same in the subgroup of primary interventions. Bipolar prosthesis was used in only 8.3% of all cases as primary intervention.

In Group II, the distribution of arthroplasty types has changed, total prosthesis being used in half of the cases with revision and bipolar prosthesis representing 14.3% of them (Figure 6).

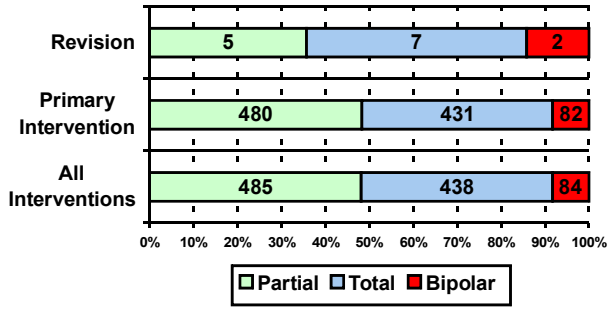


Figure 6 – ***Frequency of arthroplasty types.***

Gender distribution

The gender distribution was different in the two groups. While in Group I, more than 60% of cases were women, probably because of the more advanced osteoporosis, due to the hormonal imbalance, and the obesity that comes with ageing, in Group II men prevailed probably due to a more intense stress load of the prosthesis (Figure 7).

Concerning the bipolar arthroplasty, gender ratio in primary interventions was similar to that of the entire group of patients with primary arthroplasty. The two patients with revision using bipolar prosthesis were a 52-year-old man and a 73-year-old woman.

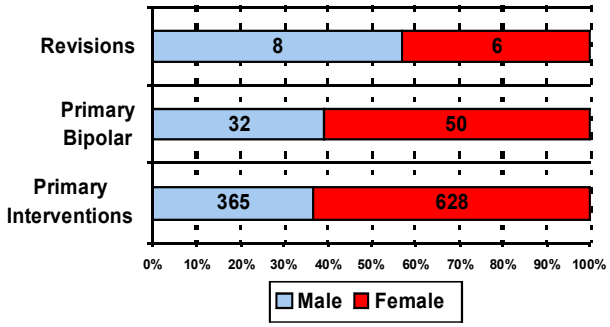


Figure 7 – ***Gender distribution and frequency.***

Age distribution

Age distribution shows, in Group I, a significant increasing trend of cases o after 50-year-old, more than a third of cases belonging to the 8th group of age (70–79 years). In the subgroup with primary bipolar prosthesis the peak is shifted to the left, being placed in the 7th decade of life (between 60 and 69 years) (Figure 8).

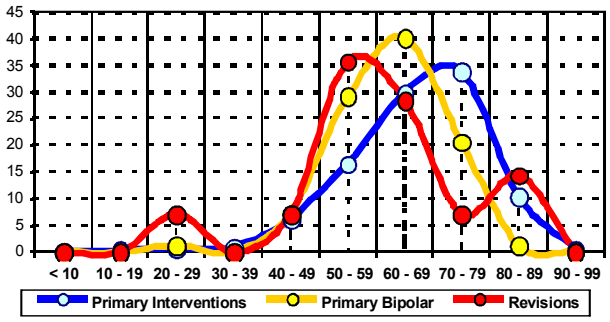


Figure 8 – ***Age distribution and frequency.***

In the group of patients with prosthesis revision, the peak of cases is placed in the 6th decade of age (between 50 and 59 years). The explanation could be a more intense stress of the joint with prosthesis in people still active.

Site distribution

The femoral neck fracture had no predilection for neither of the two sites (Figure 9).

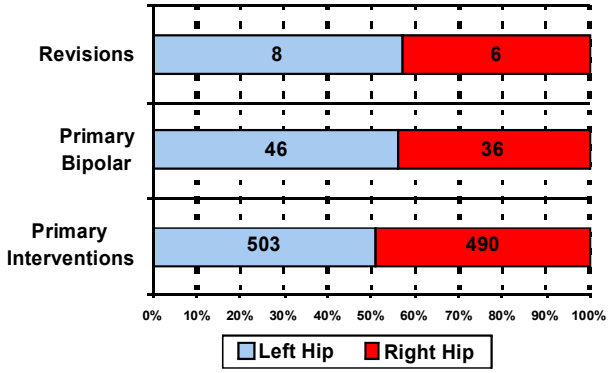


Figure 9 – ***Site distribution and frequency.***

The bipolar prosthesis was used as primary solution slightly more frequent in patients with left femoral neck fracture. Also, the revisions were necessary more frequently in the left hip joints with prosthesis (Figure 9). In both cases with revision of the bipolar prosthesis, this was placed in the left hip.

Imagistic study

Group II (patients with prosthesis revision)

All the cases of Group II – standard X-ray before the revision – showed obvious changes as acetabular rim bone thickening and demineralization of the acetabular roof (Figure 5).

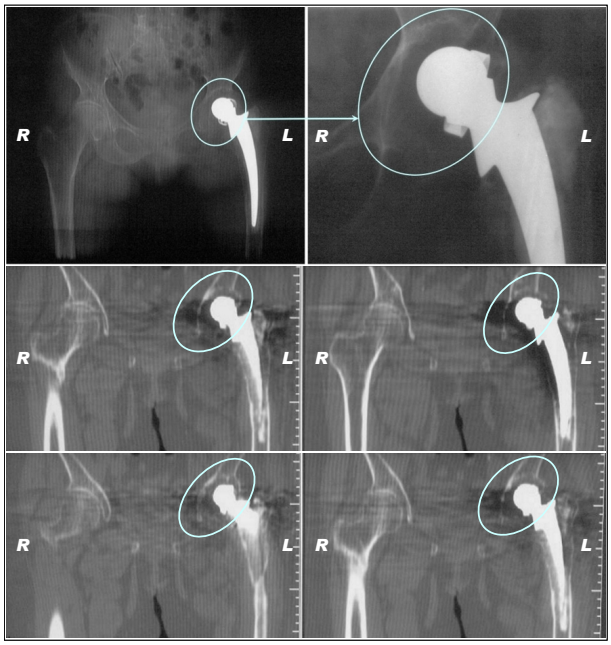


Figure 10 – ***Standard X-rays before revision.***

After revision, periacetabular and peritrochanteric heterotopic calcifications could be seen (Figure 6).

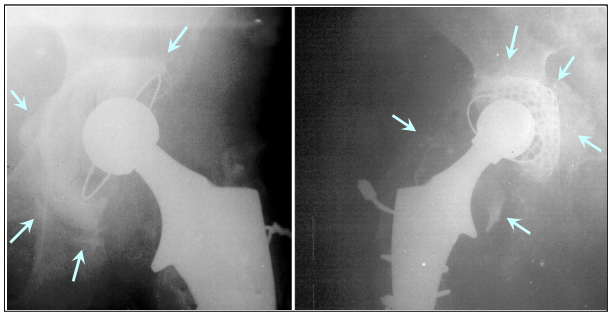


Figure 11 – ***Standard X-rays after revision.***

Group III (patients without prosthesis)

MRI images showed, in patients included in control Group III, degenerative changes of bone structure expressed by signal heterogeneity consisting of alternations of areas with hyposignal and areas with hypersignal in T1 and T2 sequences (Figures 12 and 13, d and e). The lesions included changes in acetabular perfusion, expressed by hypersignal areas (Figure 13, a and b), degenerative changes of joint cartilages, expressed by hyposignal in T2 sequences (Figure 13, d and e).

Calcifications of round ligament were present in some patients, expressed by hypersignal in T2 sequences (Figure 13c). We also identified, in some cases, areas of acetabular bone edema expressed by focal or diffuse hypersignal in STIR sequences (Figure 14).

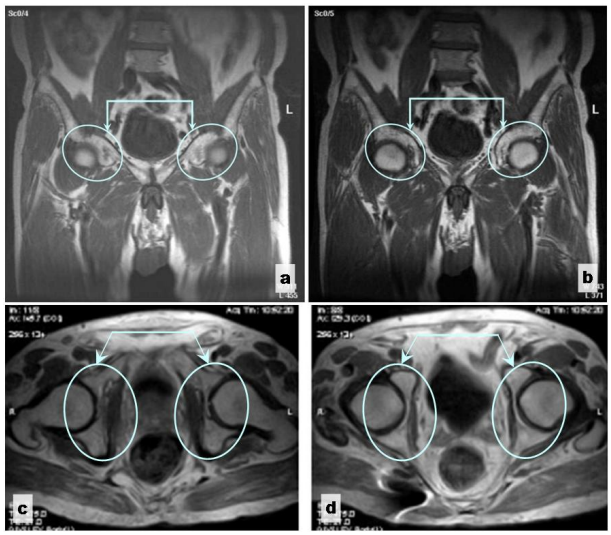


Figure 12 – ***MRI T1 sequence: (a–b): Core; (c–d): Axial.***

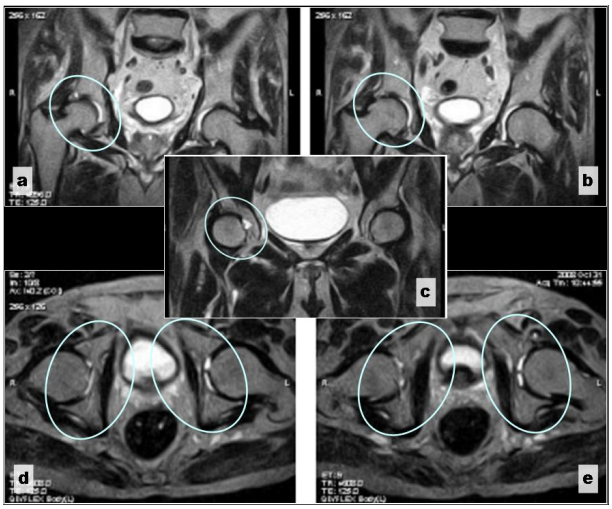


Figure 13 – ***MRI T2 sequence: (a–c): Core; (d–e): Axial.***

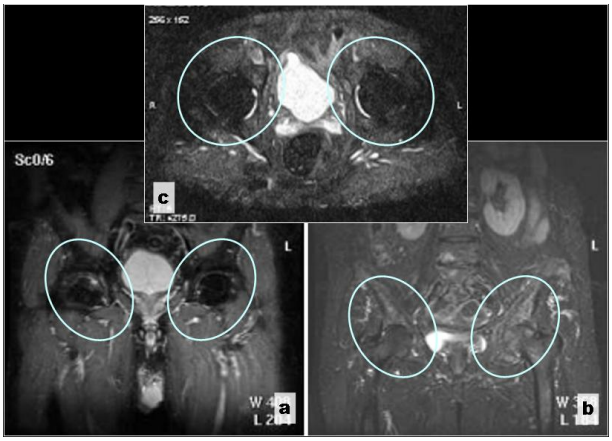


Figure 14 – ***MRI STIR sequence: (a–b) Core; (c) Axial.***

CT examination revealed a diffuse decrease of acetabular bone structure intensity, with spans shading off and enlargement of trabecular areas together with the narrowing of cortical areas (Figure 15).

These changes were observed more frequently and earlier in women than in men.

3D reconstruction on CT allowed us to determine the osseous densities (HU) in acetabular bone (Figure 16). It is known that only values below 500 HU have the meaning of a low-density bone structure, which is exposed to the risk of degeneration and fracture.

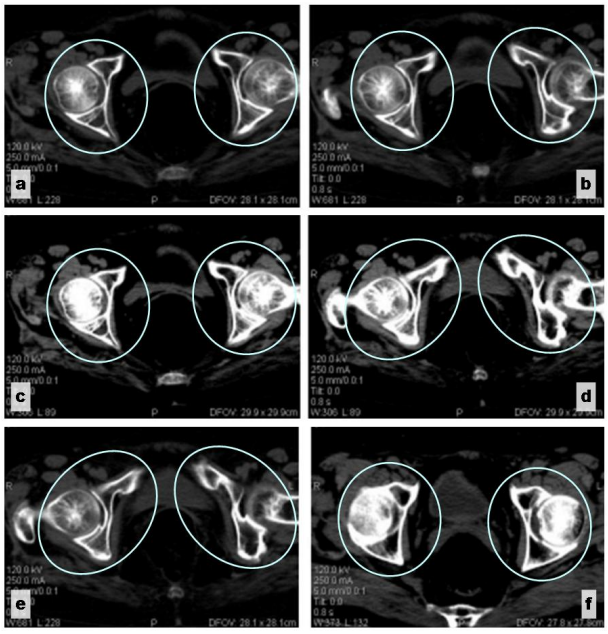


Figure 15 – ***CT axial serial sections of hip joint.***

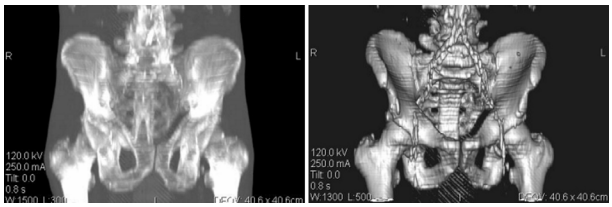


Figure 16 – ***CT 3D reconstruction of hip joints.***

Osseous density had a wide range of variation, between 217 HU and 1211 HU both in control group and revision group. In the latter, HU values had a decreasing trend with the intensity and extension of degenerative changes.

Histopathological study

The periprosthetic bone status is one of the very important elements, which need to be taken into consideration when talking about revision of the hip prosthesis. This is why, in the third part of our study, we assessed the morphological changes of the acetabular bone after the interaction with the acetabular prosthesis components, having as guide, on one side the experimental results of the simulation of stress on the acetabular bone by the bipolar prosthesis, and, on the other side, the results of the imagistic study.

The morphological analysis was performed only on bone fragments sampled according to the protocol, from Group II, which needed prosthesis revision.

As mentioned above, we analyzed separately the morphological changes seen on the bone samples taken from the area of maximal pressure of the acetabular bone, as shown by the experimental study, and those from the three acetabular areas outside this zone.

Area of maximal stress

A great variety of changes in the structure of the acetabular bone was seen in the area of maximal stress, starting with bone tissue destruction and finishing with regeneration of the acetabular bone capital.

Bone destruction

Areas of bone necrosis and lysis were observed on the bone fragments sampled from the compact bone placed in direct contact with the prosthesis. These areas of bone destruction had a linear arrangement on the acetabular surface (Figures 17 and 18).

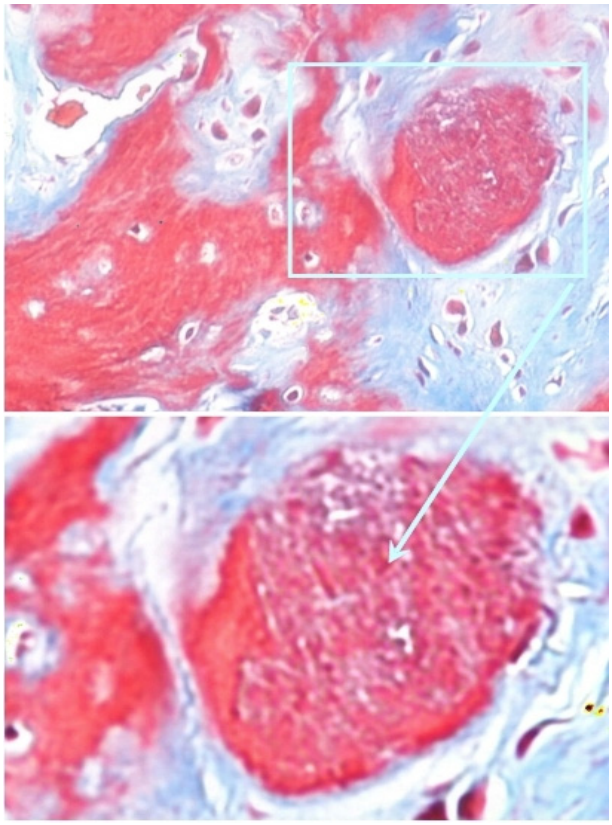


Figure 17 – ***Osteonecrosis. Above: general view, ×200; Below: detail of a necrotic focus, ×400. Masson stain.***

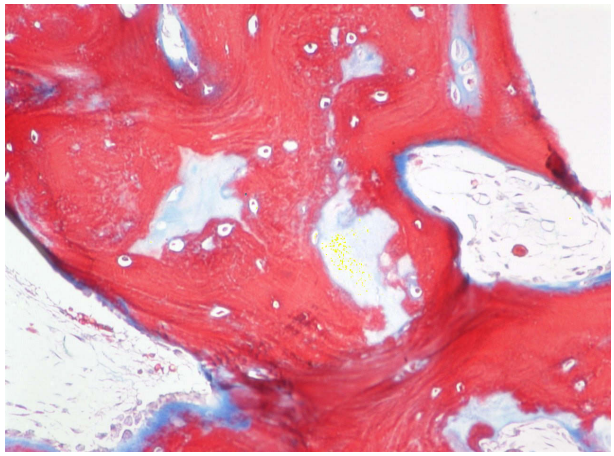


Figure 18 – ***Foci of osteolysis within compact bone areas (Masson stain, ×100).***

Areas of bone tissue replacement by connective tissue were also seen (Figure 19).

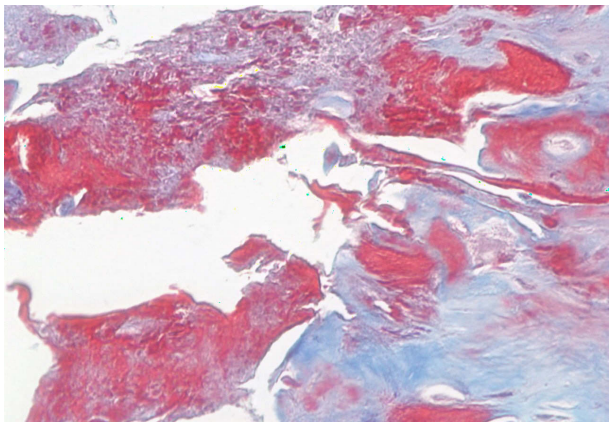


Figure 19 – *Osteolysis with collagen production around it (Masson stain, ×200).*

The connective tissue was rich in collagen fibers, and was enclosing, here and there, small areas of bone tissue.

Demineralization

Another phenomenon observed within compact cortical area of the acetabular roof was the alternation between mineralized areas and areas in which collagen armoring was low mineralized (Figure 20).

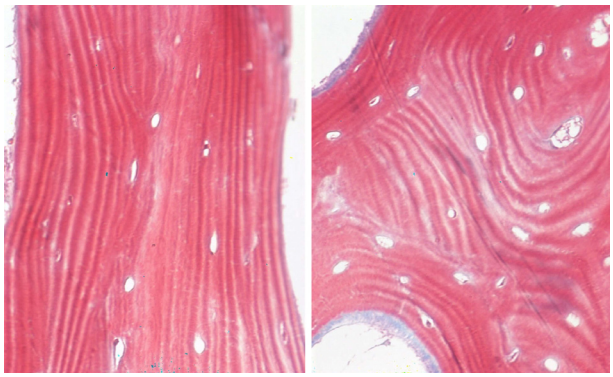


Figure 20 – *Demineralizated bone (Masson stain, ×200).*

Compact bone spanning

Another interesting phenomenon observed within compact cortical area of the acetabular roof was the presence of focal "spanning" areas, consisting of lacunae filled with connective and vascular tissue scattered within compact bone structure (Figure 21).

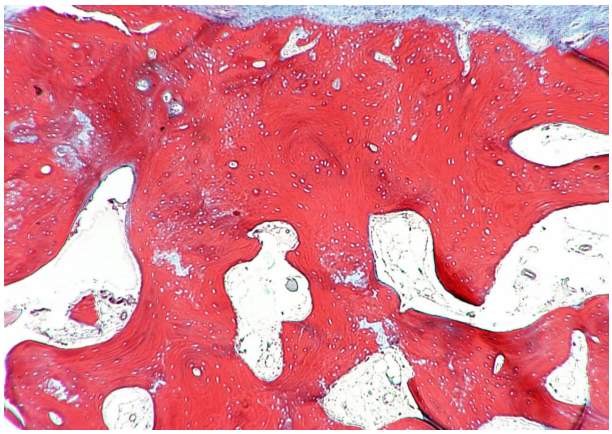


Figure 21 – *Compact bone with lacunae occupied by connective and vascular tissue (Masson stain, ×20).*

Trabecular bone "osteopenia"

Trabecular areas of acetabular bone, revealed, connected with previous observation, a process of bone thinning, consisting of thin bone areas delimiting enlarged lacunar spaces, occupied by small amounts of hematopoetic bone marrow (Figure 22).

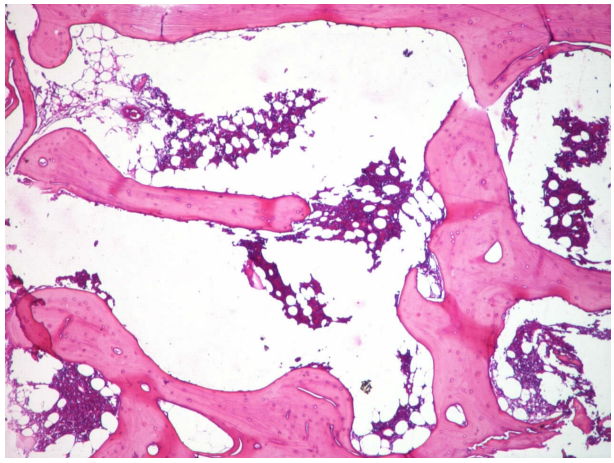


Figure 22 – *Area of trabecular bone with large spaces and thin bone areas (HE stain, ×20).*

Bone remodeling

Aside from, and together with degenerative changes mentioned above, signs of bone adaptation to the mechanical stress were seen, through a complex process of bone remodeling and restoration of the resistance structure (Figures 23–27).

A dense cellular population formed by osteoblasts and osteoclasts was seen in the areas of bone destruction and in the newly formed compact bone lacunae, cellular population that had an intense remodeling activity (Figures 23 – *left* and 24 – *right*).

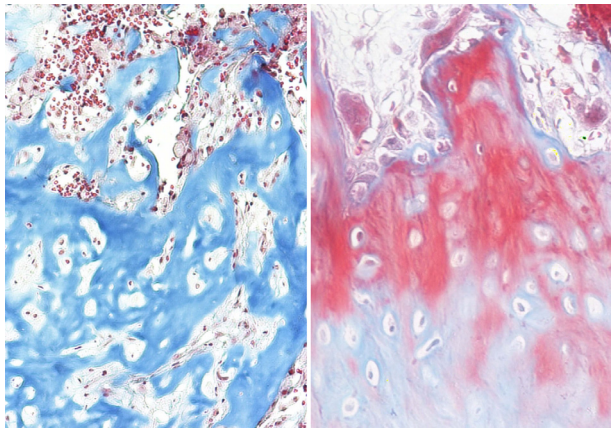


Figure 23 – *Osteoblasts and osteoclasts (Masson stain, ×200).*

Areas of destroyed tissue and lacunae are gradually filled with a collagen network, in which the fibres take gradually a lamellar disposition around some large channels, occupied by loose vascular connective tissue and coated with osteoblasts which produce this osteoid material (Figures 24 – *center* and 25).

Gradually, the collagen lamellae undergo a mineralization process (Figure 26), the diameter of the channels decreases, and thus, a new Haversian system begins to take shape (Figure 27).

Cellular density in remodeling areas

In the remodeling areas, osteocytes density had a mean value of 966 cells/mm^2 of bone section (Table 2).

Table 2 – ***Statistical parameters of osteocyte density in remodeling areas***

Statistical parameter	Value [cells/mm^2]
Average	966.2
Min.	431.7
Max.	2254.5
Standard deviation	530.7

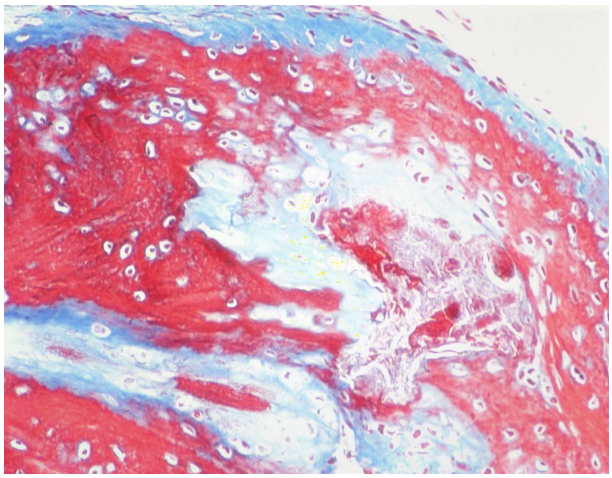


Figure 24 – ***Area of bone remodeling (Masson stain, ×200).***

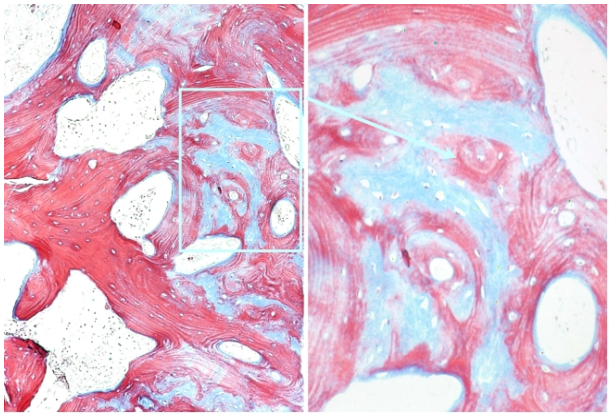


Figure 25 – ***Areas of unformed osteoid (Masson stain, ×100 and ×200).***

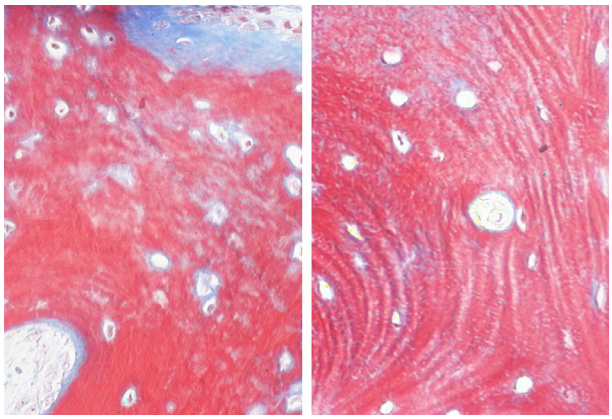


Figure 26 – ***Organizing areas with incomplete mineralization (Masson stain, ×200).***

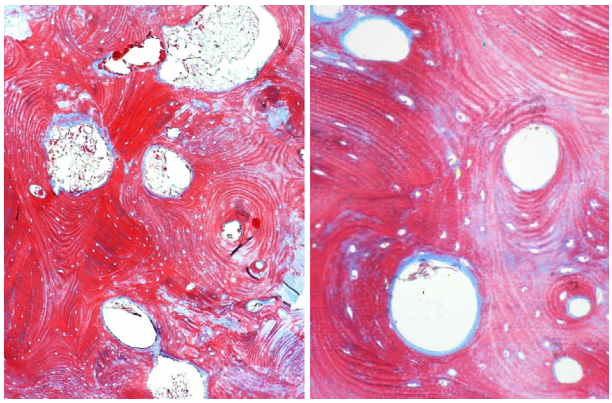


Figure 27 – ***Haversian systems with incomplete mineralization (Masson stain, left – ×40, right – ×100).***

The variation range was extremely wide, between the lowest value (431 cells/mm^2 of bone surface section) (Figure 28 – left side) and the highest value (2254 cells/mm^2 of bone surface section) (Figure 28 – right side).

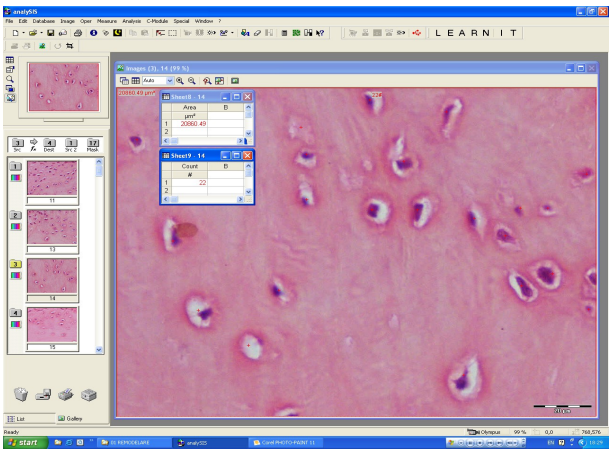


Figure 28 – ***Assessment of osteocyte density in remodeling areas – window of "measurement" module of AnalySIS Pro 3.2 software.***

The interval where most of values were concentrated (defined by standard deviation) had limits only between 436 and 1496 cells/mm^2.

Neighboring normal areas

Compact bone

In the areas placed outside the maximal pressure area, the acetabular compact bone structure was normal, (Figure 29).

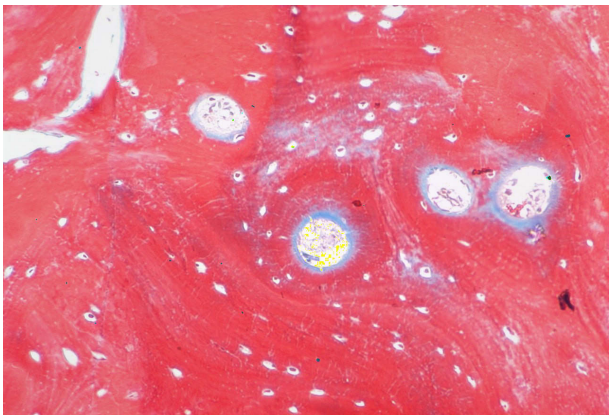


Figure 29 – ***Area of compact acetabular bone outside the maximal pressure area (Masson stain, ×100).***

Osteocyte density had in these areas a mean value of 329 cells/mm^2 of bone section (Table 3).

Table 3 – ***Statistical parameters of osteocyte density in acetabular compact bone***

Statistical parameter	Value [cells/mm^2]
Average	328.9
Min.	191.9
Max.	575.6
Standard deviation	107.8

The variation range was significantly less than in remodeling areas, the lowest value being 192 cells/mm^2 of bone surface section and the highest value being 575 cells/mm^2 of bone surface section (Figure 30).

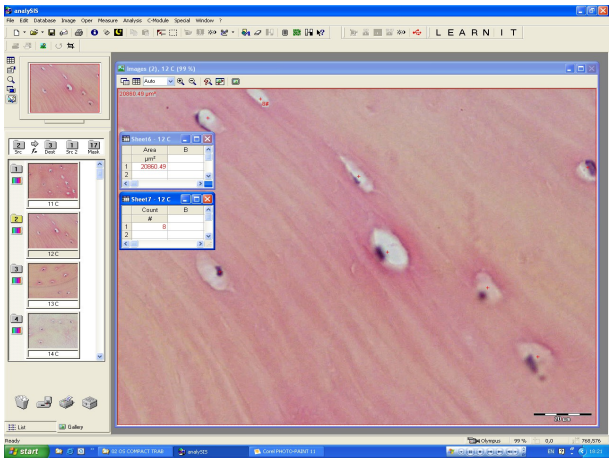


Figure 30 – ***Assessment of osteocyte density in compact bone areas – window of "measurement" module of AnalySIS Pro 3.2 software.***

The interval where most of values were concentrated (defined by standard deviation) was narrower, with limits between 221 and 437 cells/mm^2.

Trabecular bone

The trabecular areas of the acetabular roof also showed a normal structure (Figure 31).

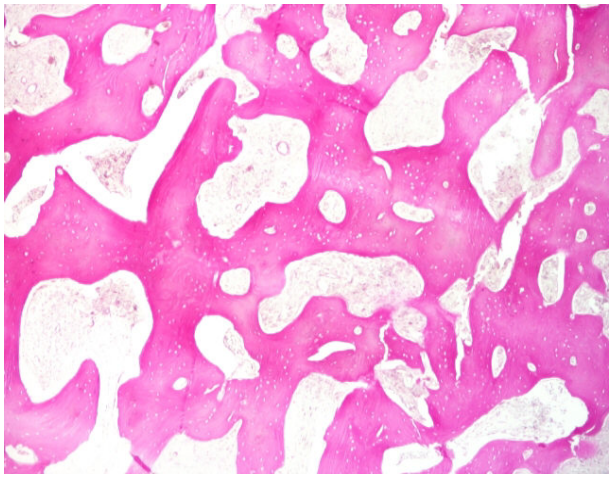


Figure 31 – ***Area of trabecular acetabular bone outside the maximal pressure area (Van Gieson stain, ×200).***

Osteocytes density was smaller than in the compact areas, having a mean value of 236 cells/mm^2 of bone section (Table 4).

Table 4 – ***Statistical parameters of osteocyte density in acetabular trabecular bone***

Statistical parameter	Value [cells/mm^2]
Average	236.4
Min.	95.9
Max.	431.7
Standard deviation	96.8

The variation range was also lesser than in compact areas, the lowest value being 96 cells/mm^2 and the highest values being 431 cells/mm^2 of bone surface section.

The interval where most of values were concentrated (defined by standard deviation) was narrower, with limits between 140 and 332 cells/mm^2.

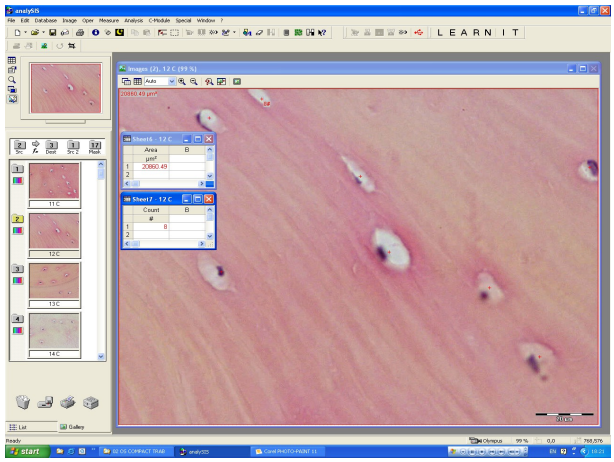


Figure 32 – ***Assessment of osteocyte density in trabecular bone areas – window of "measurement" module of AnalySIS Pro 3.2 software.***

Fibrillary profile of osseous matrix

The immunomarking with specific antibodies revealed that both in compact (Figure 33a) and trabecular bone and in remodeling areas (Figure 33b) of acetabular roof, closely apposed to prosthetic components, the fibrillary compartment of osseous extracellular matrix was represented only by type I collagen fibers (immunomarking for type II collagen fibers being negative).

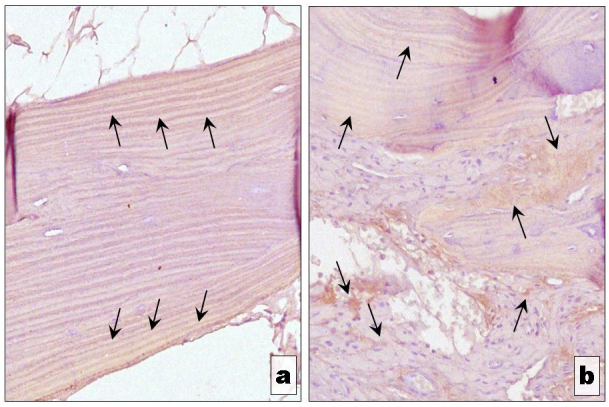


Figure 33 – ***Immunomarking for collagen I: (a) Compact bone area; (b) Remodeling area.***

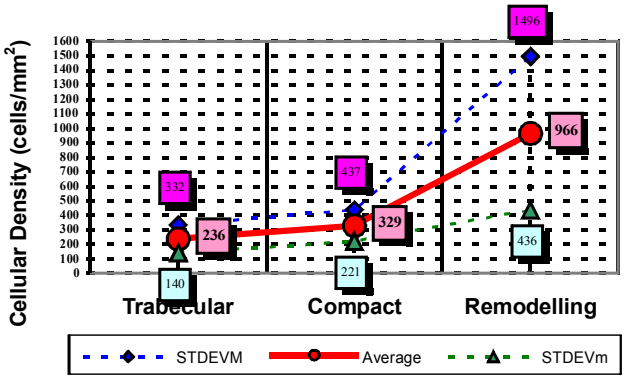
Discussion

The preliminary clinical data showed that the percentage of revisions, in a 5 years period of time, is low, mostly present in younger people that are still

active (50–59-year-old), observation that supports the idea of a more close evaluation of the acetabular bone.

The imagistic study showed a wide range of bone changes (perfusion changes, bone density changes in Housfield units, demineralization of the acetabular roof, areas of edema, osteocondensations of the acetabular rim, superior-lateral marginal osteophytosis) in elderly patients (the control group), changes present also in patients which needed prosthesis revision and confirmed by the histological evaluation.

The histopathological study confirmed the bone changes that were seen imagistically and showed that the areas of focal edema observed on the imagistic records are, in fact, areas of active connective and vascular tissue, which fill the osseous loss in order to restore the bone structure.



Finally, it seems that, while the behavior of cellular population is influenced by the presence of the prosthesis, the fibrillary structure remains homogenous, with only quantitative variations and spatial rearrangements related to cellular activity.

Conclusions

Our preliminary combined morphological results (imagistic and histopathological) revealed the existence of a real bone adaptation effort to the mechanical stress induced by the presence of the prosthesis, effort materialized through a dynamic process of bone remodeling, mostly in the area of maximal pressure.

Acknowledgements

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Microscopic analysis of different areas of acetabular roof revealed that areas where the acetabular roof was intensively stressed by the prosthetic components housed a wide range of morphological changes including both degeneration but also remodeling, while roof areas surrounding stressed area showed no significant morphological changes.

Another argument in favor of bone reaction to the stress determined by the prosthesis presence was the threefold-fourfold higher osteocyte mean density and the wide range of variation of this cellular density in areas of acetabular roof placed in close apposition with prosthetic components as compared with those of neighboring compact, respectively trabecular areas (Figure 34).

Figure 34 – ***Mean values and variation range of osteocyte density in the three different areas of the acetabular roof.***

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