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QCT as a Base of Computer Aided Diagnosis of Osteoporotical Changes

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1. Introduction

The osteoporosis is a systemic disease of bone which leads to progressive decrease of the bone mass and the changes of bone structure. As the years went by these changes became so serious that it can cause the disorders of functioning of bone in organism (bones become weak and more subject on fracture). At people suffering from this disease more often occurred the fractures e.g. in reach of hip joint and vertebral of spine. One of characteristic feature of osteoporosis is asymptomatic progress. The first signs – difficulties during move and appearing pains in the spine and in the hip joint appear when it is the big loss of bone mass and it is the large risk of fractures. Unfortunately it is a serious phase and the fractures are common – after fracture one should stabilization of places of fracture. Differences between correct tissue and tissue with osteoporosis are presented in Fig.1 [1].
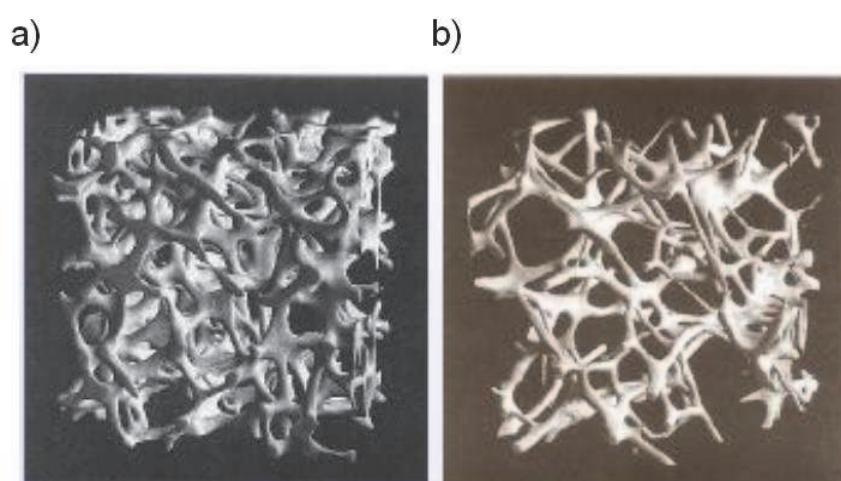

Fig. 1. Microstructure of bone: a) healthy, b) with osteoporotical changes [1]

From mechanical point of view the fracture of bone occurs in two cases:
- the correct structure of bone but the loads are so big that cause the stresses larger than stress limit,
- the disorders of bone structure caused decrease of strength properties of bone when normal activity of organism can results stresses larger than stress limit.

The attention is concentrated on the second situation (when only the physiology loading of organism can cause accidental fracture of bone) because it takes place in osteoporosis.

Very important factor is diagnosis of osteoporosis. It is a serious problem because this disease progress without symptoms. First signs appear when it is the big loss of bone mass (about 30%) and the risk of fracture is high. Comparison of radiological images of hip joint for healthy state and state with osteoporosis is shown in Fig. 2 [11].
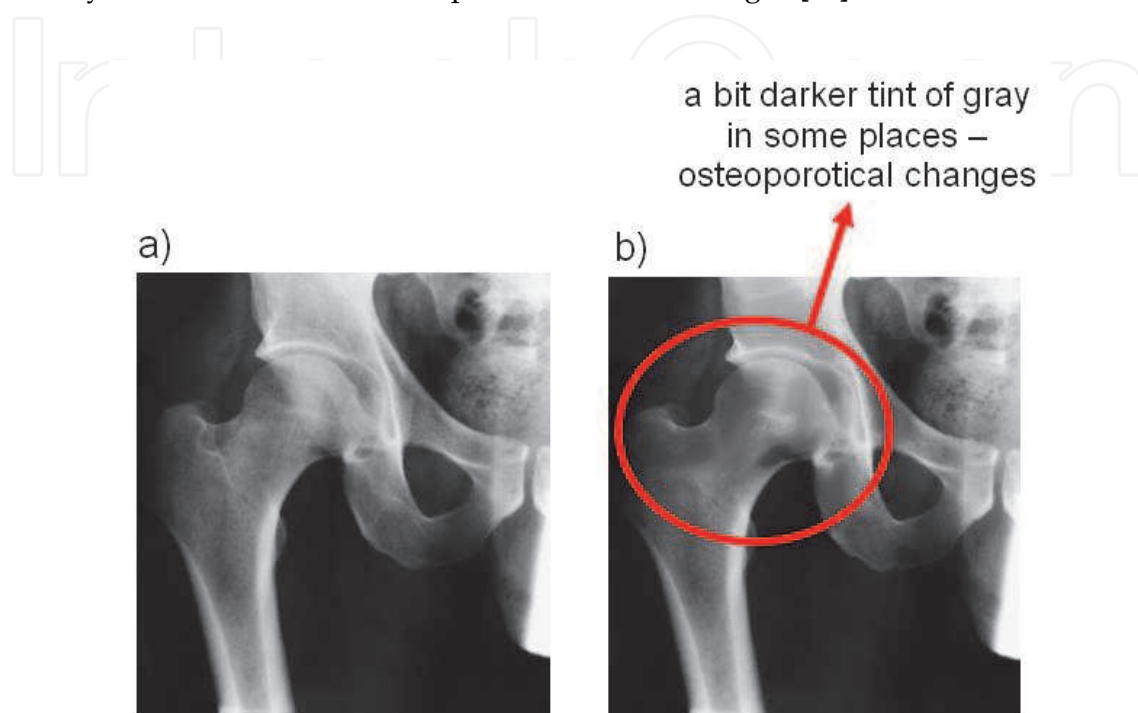

Fig. 2. Hip joint: a) correct, b) with osteoporotical changes [11]

Usually patients come to doctors when have difficulties during move and pains in spine and/or in hip joint. Unfortunately until then osteoporosis is recognized and treatment is begun. The treatment of osteoporosis usually consists of providing analgesic and stabilization of places of fractures. It would be better to prevent this disease because lack of movement is causes of weakness of bones. Knowledge of physical properties of bone tissue is helpful in diagnosing of the diseases of the bone system (especially that properties change during progress of disease).

To diagnose the osteoporosis the following preventive examinations are realized:

a. Radiology Absorptiometry (RA),
b. Roentgen Absorptiometry:
   - Single X-ray Absorptiometry (SXA),
   - Dual-energy X-ray absorptiometry (DXA),
c. Quantitative Ultrasonography (QUS),
d. Quantitative Computed Tomography (QCT).

These methods work on the base of Lambert-Beer's low which describes phenomenon of weakness of the radiation during crossing by through object. In the course of examination the part of radiation is absorbed or distracted. The intensity of radiation depends on thickness as well as the content of minerals in the bone. In result of iterative reading of photos for individual pixels, after transformation, the measurement density of whole

object is obtained. In estimate the progress of osteoporosis the largest meaning have DXA and QCT.

These are densitometry methods which risky of osteoporosis estimate on the basis of distributions of density of bone tissue. In literature there are many publications about using both of these methods in aid of diagnosis osteoporosis. Good source of knowledge about computed tomography is paper [3]. Cierniak R. characterized this method in overall way. He presented the algorithms and the principles of creating images. He described also applying measuring techniques as well as CT scanners. Computed tomography is inverse problem – on the base of gathered data the model is created (on the basis of information about absorbed radiation in individual slice of scanning the images are generated). Adams J. E. in [2] described in details QCT. Authoress go into genesis of these method, its development, clinical applying, in particular diagnosis of osteoporosis. She presented different variety of QCT and described density phantoms Adams J. E. compare QCT with other methods and gave example when QCT is more useful: in case when we can obtain more information about researched bone (because images from QCT after conversion are good sources of information). Sawada K. et al. in papers [16] and [17] pay attention that if we want to find physical properties of bones same places are more useful (e.g. spine or hip joint) and same places are less useful (e.g. wrist or limbs). Engelke K. et al. in paper [4] presented the official state the International Densitometry Society about applying of quantitative computed tomography and peripheral quantitative computed tomography in diagnosis of osteoporosis at adults person. Authors pay attention that although the dual energy x-ray absorptiometry is often used in recognition of osteoporotical changes, in some cases better solution is applying the QCT. Engelke K. et al. emphasize that important matter is calibration of density phantom (the more accurate calibration the better results from tomography). Authors put many details about methods of performing QCT examinations, technical parameters of tomographs as well as gave advice to interpreting of results from tomography. On the base of the papers: Adams J. E. [2], Engelke K. et al. [4] and Nayak S., Roberts M.S. & Greenspan S.L. [14] we can say that when we compare both of these methods: DXA and QCT, more precise data of bone density is from QCT (from DXA we obtain "surface density" – in g/cm^2, from QCT "volume density" – in g/cm^3). Besides, in DXA is more difficult to distinction the kind of bone at the densitometry images. Second reason is the fact that data from QCT is more useful to create numerical model. In our case better solution is to use quantitative computed tomography – that's why we applied this method.

2. Quantitative computed tomography

2.1 Description of QCT

In this method the tomograms from CT are used to analyze the mineral density of bone. Through using the composition of projection images from different directions one can get cross-sectional and solid images in all researched structures (Fig. 3) [19]. Tomograms consist of individual voxels. Each voxel is characterized by coordinates x, y, z and color in gray scale. On the base of amount of radiation (absorbed in different places) one can determined density in these places with exact to one voxel.

QCT differs than standard approach occurrence of density phantom which is X-rayed together with patients. The phantom is composed of regions representing specimens of bone density in Hounsfield Units. The density phantom is presented in Fig. 4.
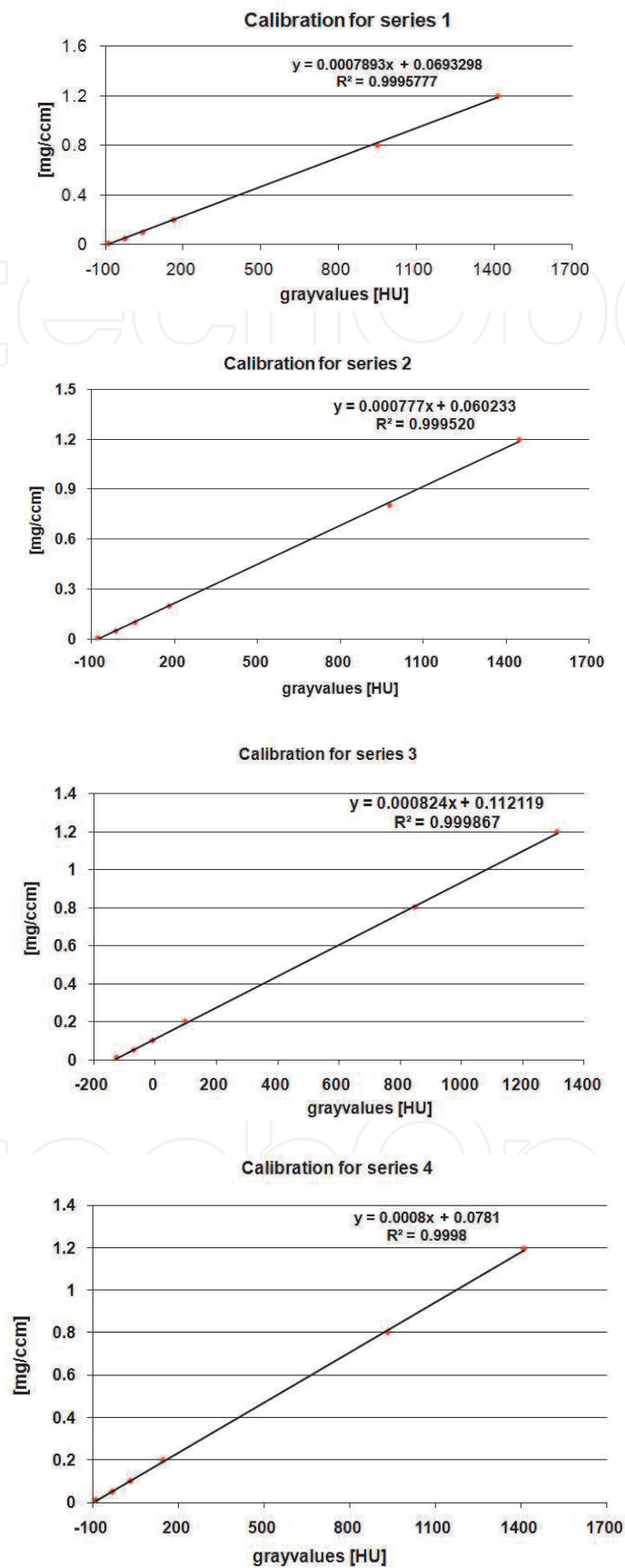
Here, phantom is composed of six specimens. On the base of these standard density the calibration curve is drown. Formula of this curve enables to determinate the density for each voxel of researched bone. The calibration curves for four series were presented on Fig. 5.

Fig. 3. Reconstruction images by analytical method with filtration [19]

Fig. 4. The density phantom in different views

Fig. 5. The calibration curves for different series

2.2 Data from QCT

After radiological examination the images of researched structure are obtained. In the next step these data are conversed to receive information about analyzed bones.

The general course of transforming data is as following:

1. Performing of tomography examinations. As a result the images (sections in different places) of analyzed object are received.
2. Analyzing the X-ray photographs by use specialist software (the dependence between quantity of the absorbed radiation and the radiological density in bone tissue is used). The exemplary tomograms of pelvic bone were presented in Fig. 6.

density phantom

Fig. 6. Exemplary images of human pelvic bone from QCT

3. Standardizing obtained density to Hounsfield scale – HU:

$$1HU = K\frac{\mu_p - \mu_u}{\mu_u} \tag{1}$$

K – amplification factor of images,
μ_p – absorption factor,
μ_u – absorption factor of reference object,

4. On the base of HU density determining the density of bone tissue [7]

$$\rho = 1.122 \cdot HU + 47 \tag{2}$$

5. Delimitation of the material properties of bone tissue, especially elastic modulus (on the basis of experimental research the dependences between bone density and material properties were developed) [2], [14]. It is important step because in numerical simulations we need material properties from the beginning.
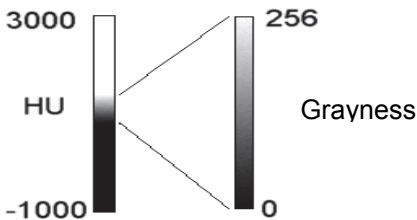
$$E = 1.92\rho - 170 \tag{3}$$

Fig. 7. The gray scale and the Hounsfield Units

2.3 Conversion of data from QCT to create numerical model

During modeling of biological structures occur difficulties connected with representation of geometry and subordinating of material properties to numerical model.

Bones have complicated and non-regular structure. Additional difficulty is mapping of internal structure of bone (there are problems with delimitating of thickness of each layers). Traditional building of geometry in some cases is very hard, time-consuming and created models are over-simplificated. For these reasons during creations of biomechanical structure one use radiological images – on the base data from radiology (e.g. computed tomography) the information about structure of bone are received. If we have section preparations we will obtain geometry from measurement coordination machine, but for living patients it is impossible. As far as problems with representation of geometry were in large part solve in as much determination of material properties to cause bigger difficulties. Biomechanical structures usually belong to non-homogenous and anisotropy material. Reference point is material parameters determinate in experimental researches but in organism conditions they may have different values. Another problem is to estimate material properties during pathological changes. Recognition of these changes and local non-homogenous is a large challenge for medical doctors, biomechanics and manufacturers of diagnosis devices.

For the purpose of assignation material parameters obtained from QCT to numerical model the in-house procedure was used. On the base of QCT images (with resolution 512x512) the matrixes were get.

For every CT image the matrix of values of elastic modulus is determined. When we combine all matrixes for one set of CT images in one big matrix we will prescribed values of elastic modulus in one file. The next step is subordinating values of Young modulus from this matrix to numerical model. Demonstrative show process of converting images from tomography is presented in Fig. 8.
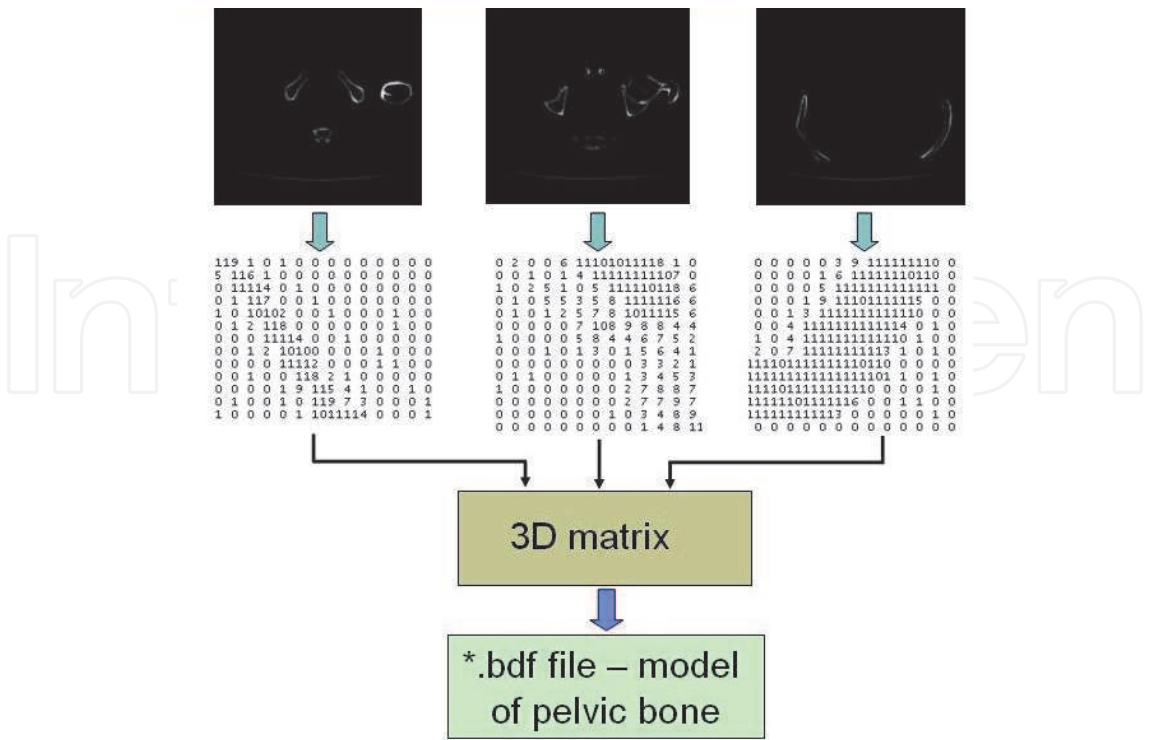

Fig. 8. Procedure to converting images from QCT to create numerical model

Additionally the text files with coordinates of nodes of researched model are created: x.txt, y.txt, z.txt.

Algorithm of the program consists of following steps:

1. Creation of 3D table: [u, v, w] on the base of file combined.txt: coordinate **u** represents coordinate **x**, **v** represents **z** and **w** represents **y** in numerical model.
2. Modification of input file to MSC.Nastran: insertion value of elastic modulus on the base of tomography to numerical model. In this way come into being FEM model in which in every finite element the individual material parameters were subordinated.

The exemplary image from QCT and equivalent cross-section in numerical model are presented in Fig. 9.

Fig. 9. Tomography image and cross-section in numerical model

Exemplary part of matrix with values of Young modulus is shown in Fig. 10.

Fig. 10. Fragment of table with values of elastic modulus obtained from tomography [GPa]

2.4 Quality of images from QCT

Very important problem is quality of images from radiology examinations. On the base of obtained information, it is deducted about patient's state, disease's progress and it is possible to plan the treatment and check correctness of therapy. In case of QCT, when dates are often converting, quality of tomograms has special meaning. There are a few important features of images, which decide about useful in medical diagnostic: contrast, sharpness, resolution, noise-to-signal ratio, artifacts and distortion of signals.

Occurrence hums and disturbances is one of the characteristic features of signals. In dependence on method there is different kind of hums. Increase of hums level lead to lowering of visibility and the decrease of contrast. In a consequence photographs gives little information and are less useful. Hums are observed on the every stage of transformation data and it would be the best if minimization of disturbances started from the very beginning of creation of images and lasted during whole registration process of the data. Hums and disturbances can influence on incorrect interpretation of photographs. Influence of hums can be limited by using the low-pass filters and locally enlarging the contrast. Unfortunately during reducing of disturbances it can lose the part of information which will influence on level of medical content.

The artifacts are others problems during conversion of photographs from radiology. These are unwanted feature of images appearing in medical modalities. The artifacts do not reflect the properties of researches structures but they are the result of accidental factors. In Fig. 11 the comparison between normal image and image with artifact is shown [4].
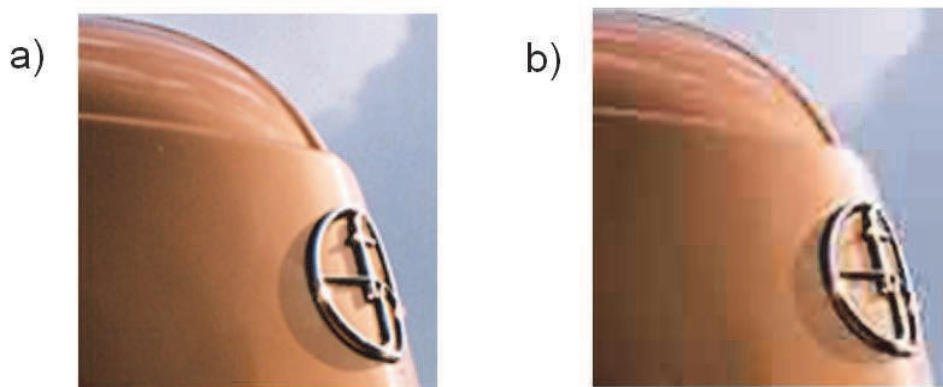

Fig. 11. The differences between: a) correct images and b) images with artifacts [4]

Sometimes it does not influence significantly on perception of diagnostic information, however in some cases it can limit accuracy of interpretation or even mislead (the artifacts pretend features of living structures). Many different factors can cause formation of artifacts e.g.: methods of data processing, algorithms of creation of images, movements of patients or shift of X-ray lamp. During QCT examinations frequent artifacts are appearing defects on boundaries of areas with different density – in images are local decrease of sharpness and contrast, the rise of shadows or the exaggerations. In a consequence it can cause to incorrect estimation of material properties (Fig. 12) [19].

3. Numerical model of human pelvic bone

After performing tomography examination next step is to convert obtained images to get effort state of bone. Data from QCT was used to create the numerical model of human pelvic

bone. First, the geometry of the model should be prepared. The geometry from tomography or from measuring coordinate machine can be applied.
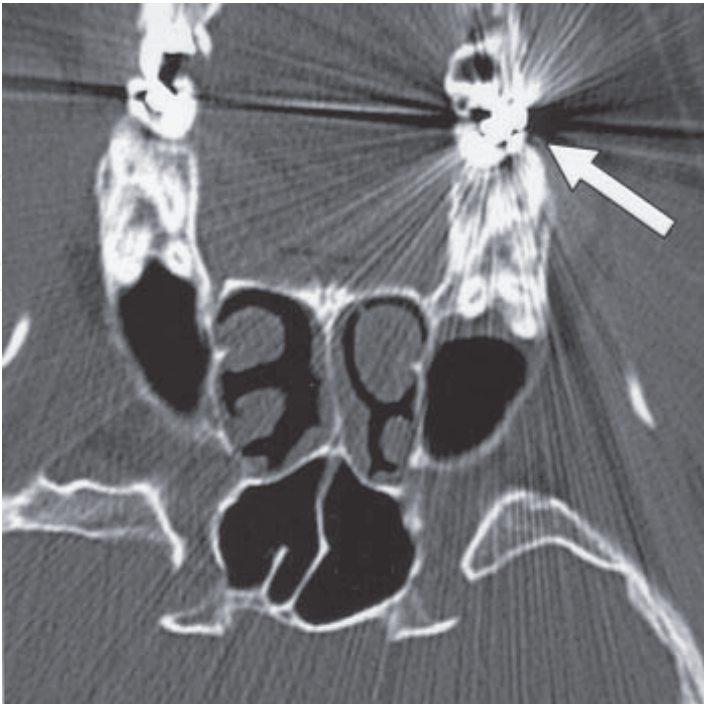

Fig. 12. The artifact caused by metal filling [19]

The model consists of three main parts:
- pelvic bone (compact and trabecular tissue),
- endoprosthesis of hip joint (cement layer and artificial acetabulum),
- femur head (metal or ceramic).

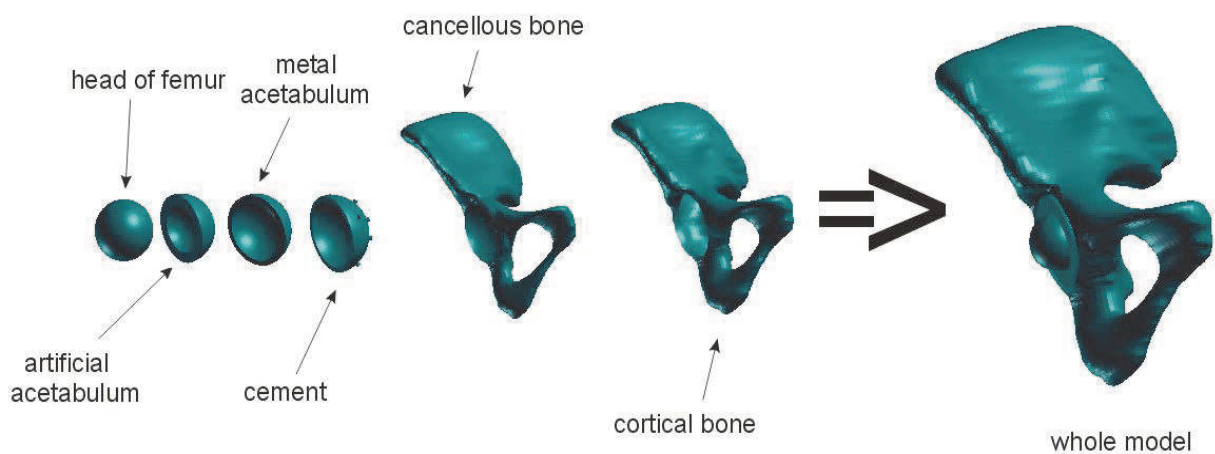The components and whole model of human pelvic bone are presented in Fig. 13.

Fig. 13. Component of model of pelvic bone

Characteristic feature of the model is subordinating individual material parameters to each finite element – this represents non-homogenous structure of bone and changes in pelvic bone during osteoporosis (model is closer to real conditions).

After completing prepared model on boundary conditions (it is presented in Fig. 14), the calculations on the base of FEM are performed.

Important problem is to determine the changeability of material properties in numerical model. It was achieved in two approach – they became describe later.

Fig. 14. Meshing and boundary conditions of the model

4. Data collection

4.1 Using of clinical data

Calculations are performed on the base of linear static according to Huber-Von Mises criterion, using data prescribed in chapter 2.3. Important fact is assuming material parameters on the basis of images from tomography.

In Fig. 15, 16 and 17 the distributions of reduced stresses, strains and displacements are presented. The maximum reduced stresses (Fig. 15.) and strains (Fig. 16.) appear in the head of femur and in the joint between sacral and pelvic bone.
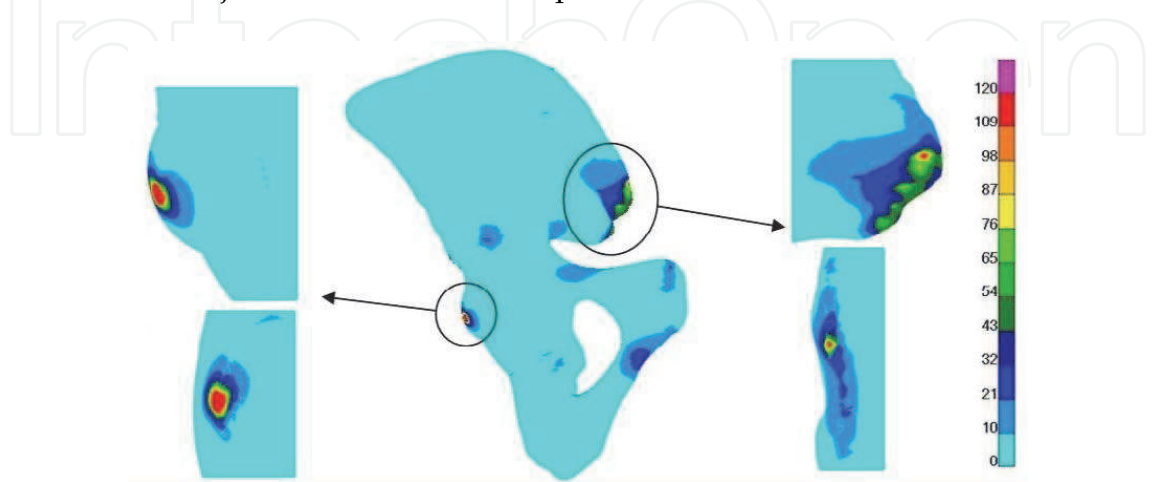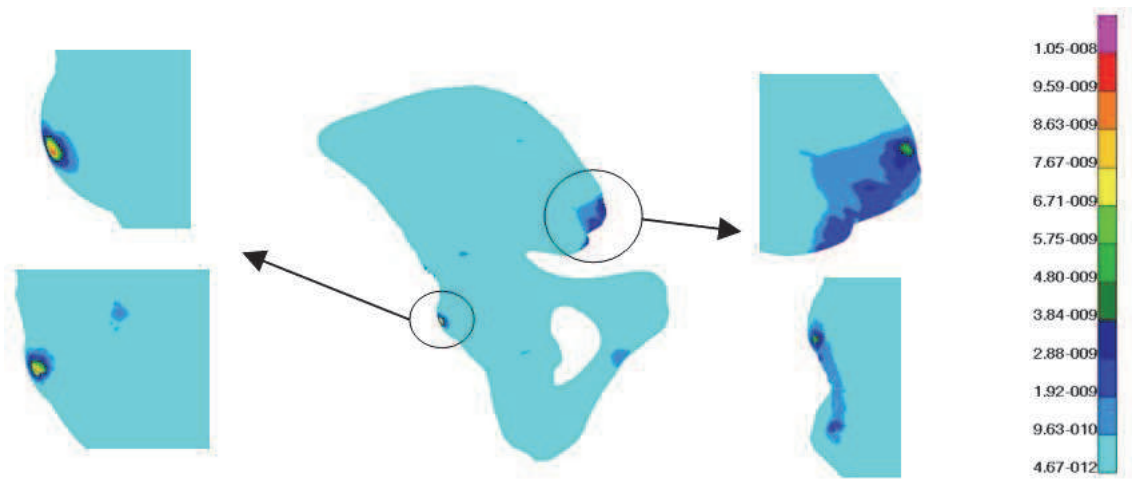
Fig. 15. Distributions of reduced stresses [MPa]

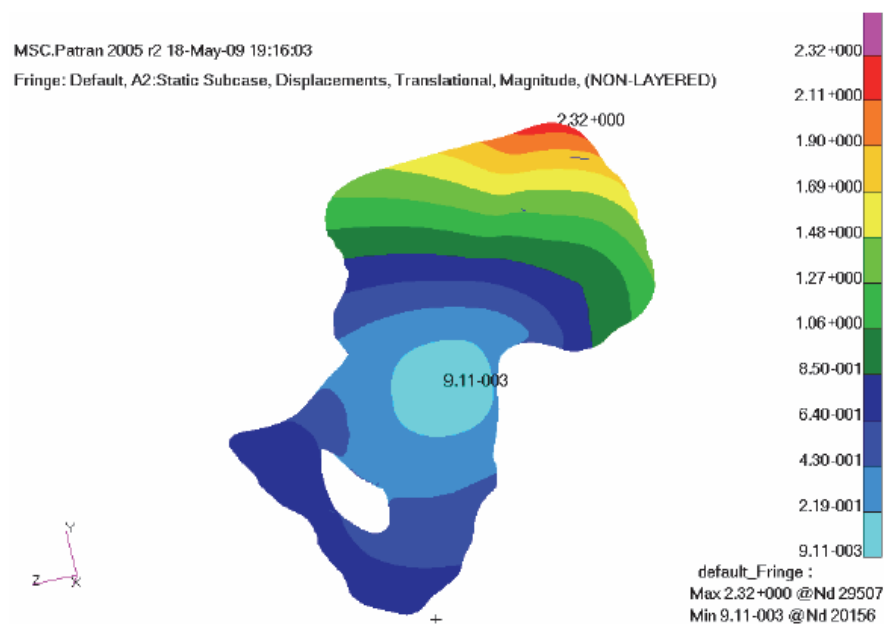Fig. 16. Distributions of reduced strains

Fig. 17. Distributions of displacements [mm]

4.2 Numerical simulations of osteoporotical changes

In view of difficulties and limited access to images from tomography the numerical models containing osteoporotical changes were created also in different methods. Second approach consist of division whole model to subregions – groups. Cortical bone was divided into five subregions, in each subregions elastic modulus is in the some range of value. In Fig. 18 the subregions of cortical bone are shown:
- Pubic symphysis and joint of pelvic and sacral bone: 15000 –15600 MPa (violet),
- surroundings of acetabulum: 13000–13500 MPa (red),
- upper part of ilium ala: 12000–12600 MPa (brown),
- central part of ilium ala: bone: 13500–14000MPa (yellow),
- ischium and pubis: 14000-14500 MPa (blue).

Cancellous bone was also divided into a couple of part (Fig. 19):

- External layer of bone (2000-2600 MPa):
- Surroundings of acetabulum (green),
- Upper and lower part of bone (brown),
- Internal layer of bone:
- Surroundings of acetabulum: 250–300 MPa (blue),
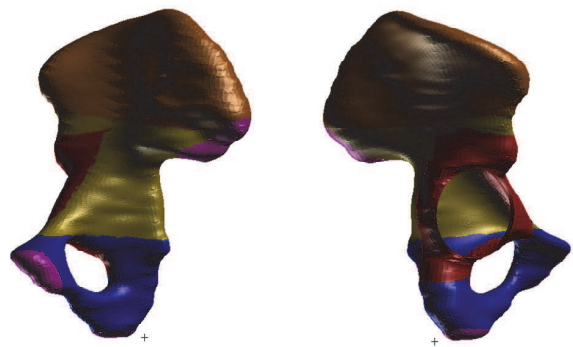- Upper and lower part of bone: 200–250 MPa (yellow).
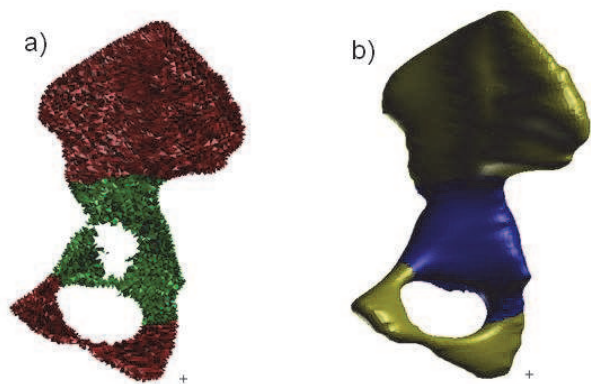

Fig. 18. The subregions of cortical bone

Fig. 19. The groups of cancellous bone: a) external layer, b) internal layer

In each of these groups values of elastic modulus in individual finite element was determined on the base of decreasing of bone mass and the range of changeability of Young modulus (Fig. 20).
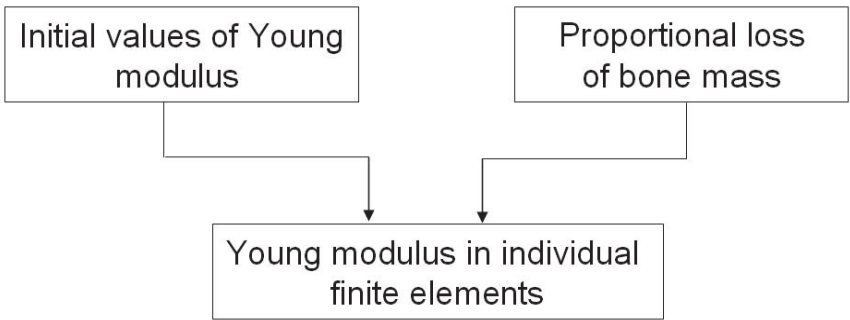

Fig. 20. Determining of elastic modulus in individual finite element

During calculations the following relationship were used:
- for cortical bone – conception of Weinans [12]:

$$E = 4.249 \cdot \rho^3 \qquad (4)$$

- for cancellous bone – conception of Mow and Hayes [12]:

$$E = 2.195 \cdot \rho^3 \qquad (5)$$

where:
E – elastic modulus,
ρ – radiological density of bone tissue.
It is possible to change these formulas to another and computation distribution of material properties according to different relationships.
The exemplary distributions of stresses, strains and displacements were presented in Fig. 21, 22 and 23. The maximum reduced stresses (Fig. 21.) and strains (Fig. 22.) appear in the head of femur and in the joint between sacral and pelvic bone.
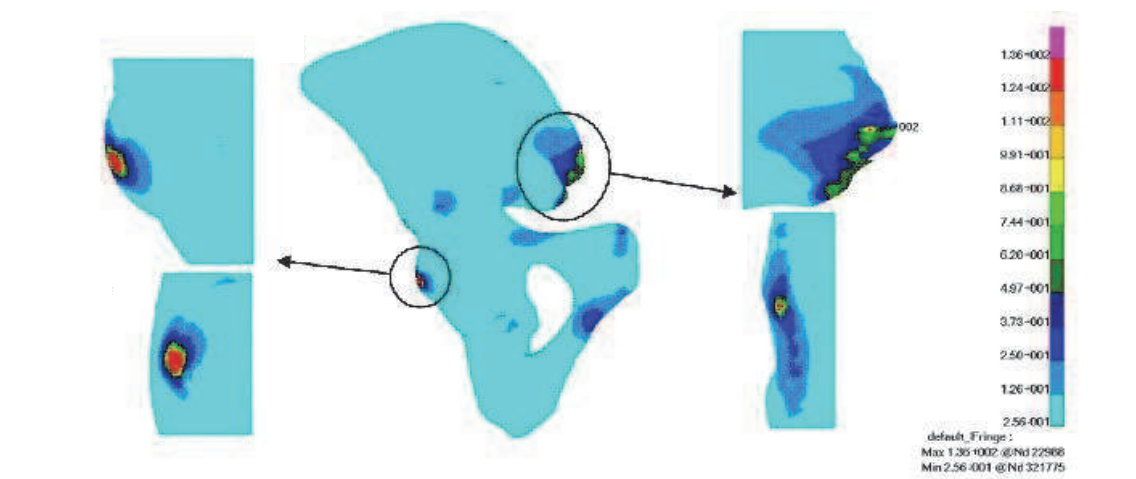

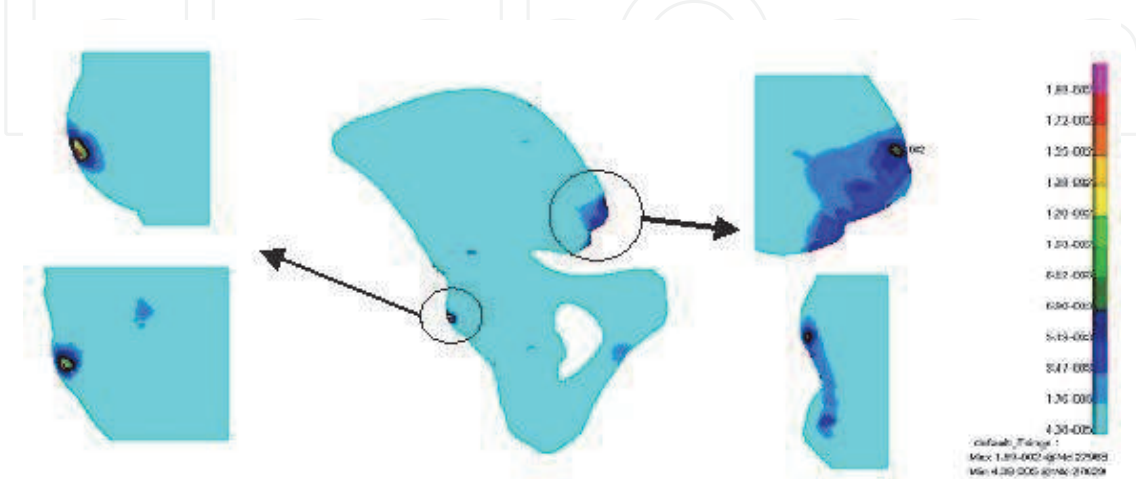Fig. 21. Distributions of reduced stresses [MPa]

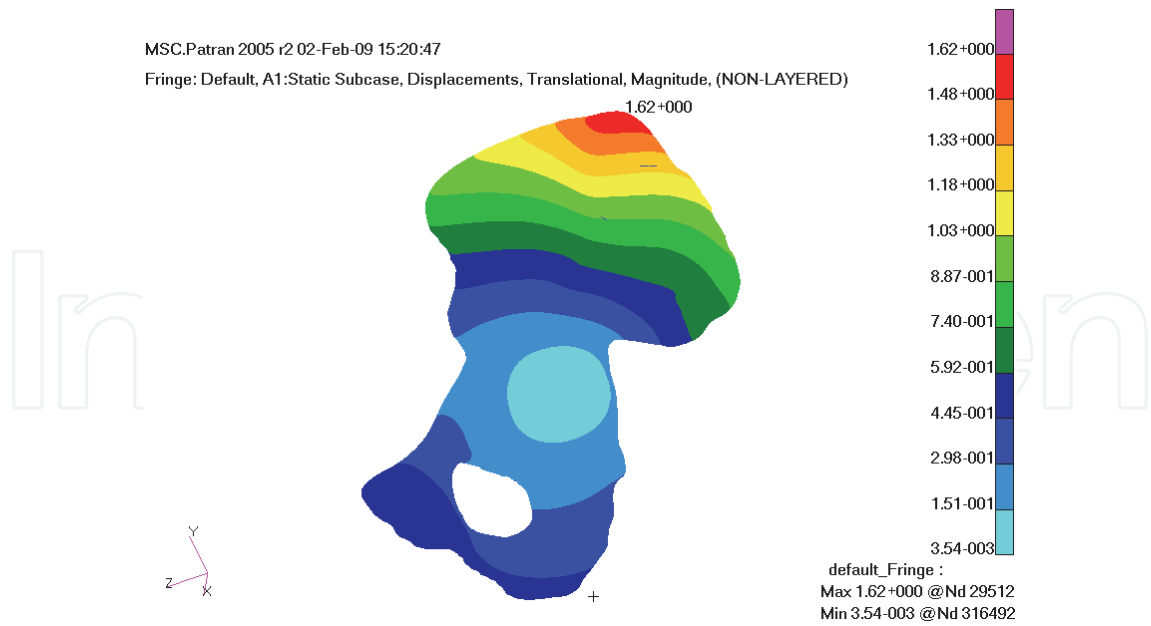Fig. 22. Distributions of reduced strains

Fig. 23. Distributions of displacements [mm]

Some results of numerical simulations are put into Table 1 and Table 2. The maximum value of displacement and reduced stress in dependence on loss of bone mass (in percent, in upper part of ilium ala) are shown. Next, in Table 2 the same dependence is shown when the loss of bone mass appear in pubic symphysis and sacral joint. Additionally, the value of maximum strain is prescribed.

loss of bone mass [%]	u_{max} [mm]	σ_{max} [MPa]
0	1,38	157
10	1,51	149
20	1,68	140
30	1,89	144
40	2,16	154
50	2,49	164

Table 1. Displacements and stresses for loss of bone mass in upper part of ilium ala

loss of bone mass [%]	u_{max} [mm]	σ_{max} [MPa]	ε_{max}
0	1,38	157	$8,00 \cdot 10^{-3}$
10	1,49	148	$1,14 \cdot 10^{-2}$
20	1,62	137	$1,50 \cdot 10^{-2}$
30	1,79	130	$2,00 \cdot 10^{-2}$
40	1,98	144	$2,70 \cdot 10^{-2}$
50	2,22	162	$3,67 \cdot 10^{-2}$

Table 2. Quantities for loss of mass in pubic symphysis and joint of pelvic and sacral bone

In Fig. 24. the exemplary graph showing relationship between decreasing of bone mass and stresses and displacements. To infer about dangerous state in bone system one should take into attention all of quantities characterizing effort state, e. g. for point A, B and C

information about stresses only is not unambiguous (it is not enough information about loss of bone mass) however when we also consider displacements we can determinate how loss of bone mass is in each points.
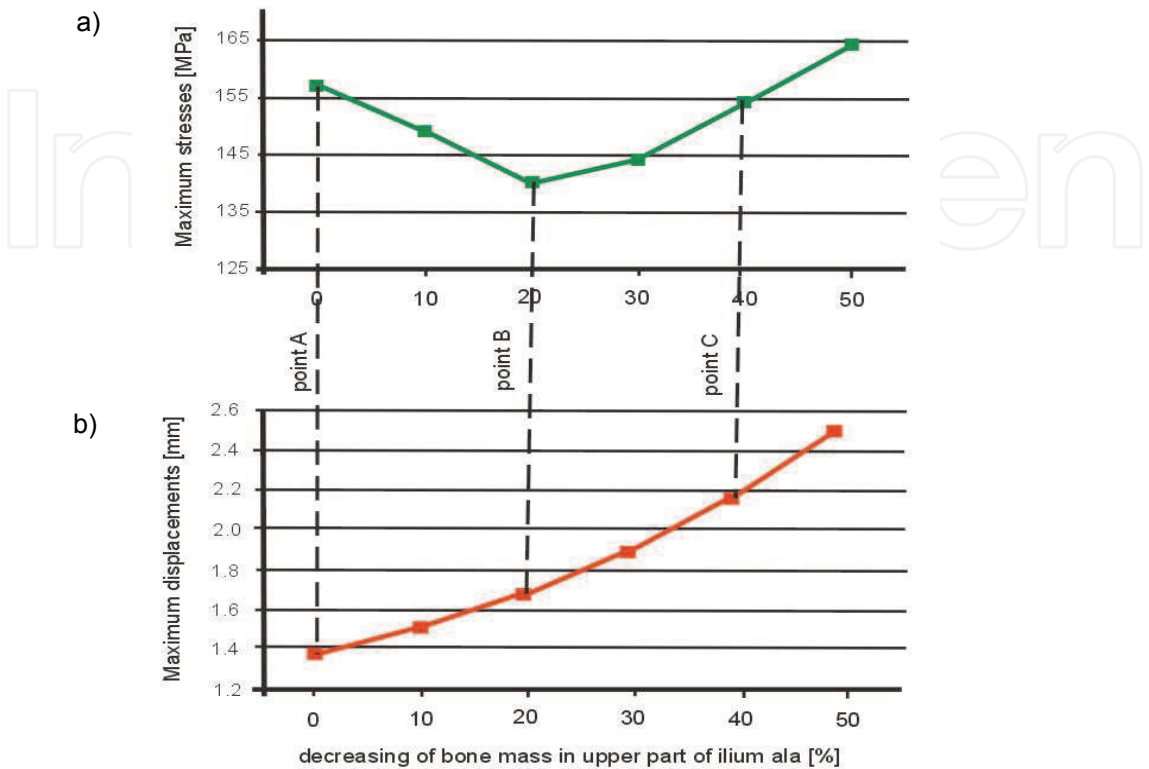

Fig. 24. Relationship between loss of bone mass and: a) stresses, b) displacements

5. Aid of diagnosis osteoporosis in pelvic bone

5.1 Data base

After QCT examinations the tomograms of researches structure are obtained. At the first, it is necessary to determinate the radiological density. To transformation of that quantity one should rescale it to HU. The next step it is delimitation the density of bone tissue (on the base of density in HU). By using relationship between density of bone tissue and material properties it is possible to calculate material parameters of bone tissue in each voxel. From the other hand, on the base of QCT data it is possible to create the geometry of numerical model. When the model is prepared the material properties are inserted and the strength calculation (according to FEM) is performed. On the ground of obtained results (distributions of stresses, strains and displacements) one can get to know about effort in researched bone.

When the large amount of QCT examinations will be realized (the set of data will be converted and strength calculations will be performed) it will be possible to create the base of data. This base will be aid detection of osteoporotical changes in human pelvic bone. This data base one can compare to table – matrix which consists of CT photos: column symbolize images for individual patients, row vector places where images were done. The base one have to divide into two main parts: QCT images and numerical simulations. General structure of data base is shown in Fig. 25.
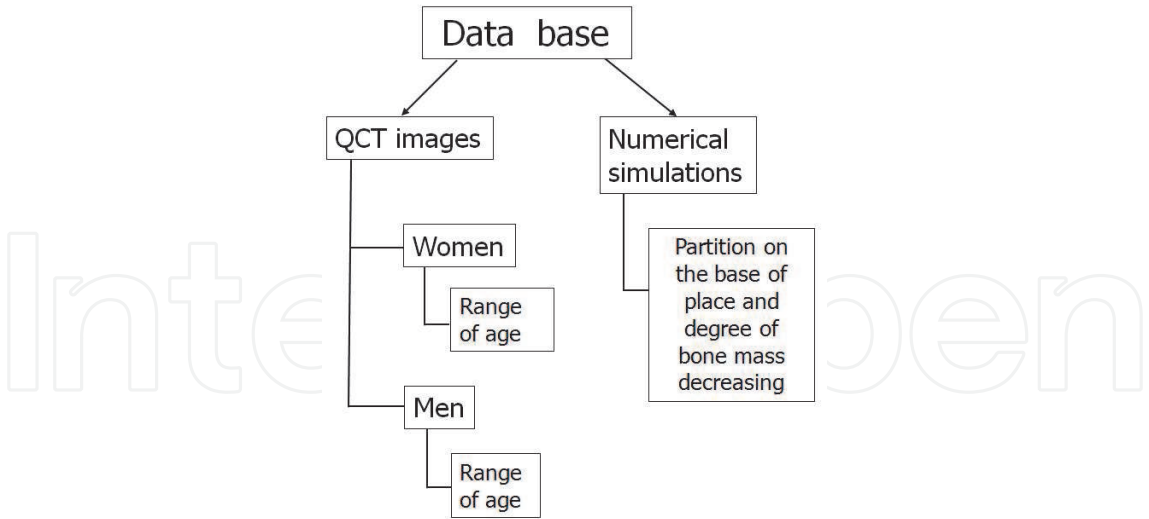
Fig. 25. Schematic structure of data base

The data base makes up folders with suitable data and group with the correct order. The fragment of the base is presented in Fig. 26.

Fig. 26. The part of data base

5.2 Procedure to aid of diagnosis osteoporosis
After building the numerical model the next step of work is to develop procedure to aid of recognizing osteoporotical changes in pelvic bone.
The general principle is as follow: after radiology examination it takes place searching to find the most similar images (searching CT photo from data base). When these images are found the whole model with strength parameters is assigned. Next the results (from strength calculations) are analyzed. As a consequence, particular images from QCT are subordinated to effort of bone. In case of need it is possible to return to searching of base and analyzing the larger number of data. The simplified block diagram of the program is presented in Fig. 27.

```
            ┌─────────────────────────┐
            │ Determination of number │
            │    and format of data   │
            └───────────┬─────────────┘
                        ↓
            ┌─────────────────────────┐
      →────→│    Assignation of data  │
      │     │        from base        │
      │     └───────────┬─────────────┘
      │                 ↓
      │     ┌─────────────────────────┐
      │     │ Identification of numerical │
      │     │          model          │
      │     └───────────┬─────────────┘
      │                 ↓
      │     ┌─────────────────────────┐
      │     │ Analyzing of results from │
      │     │   strength calculation  │
      │     └────┬──────────────┬─────┘
      │          ↓              ↓
┌─────┴──────────────┐  ┌──────────────┐
│ Return to searching│  │  Diagnosis   │
│      of base       │  │              │
└────────────────────┘  └──────────────┘
```
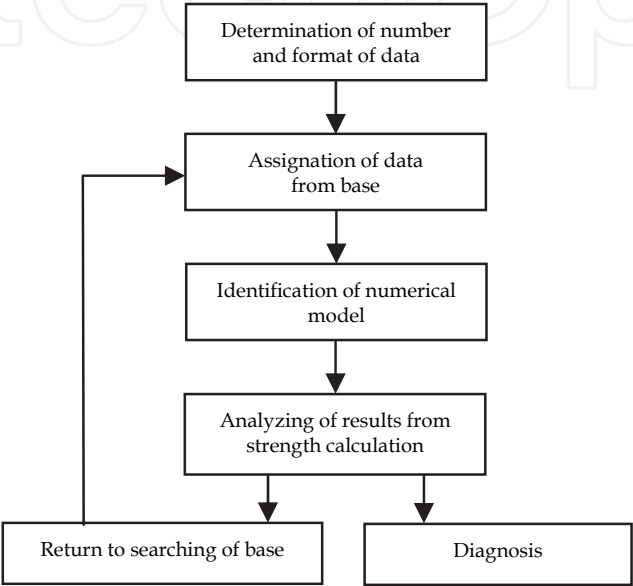
Fig. 27. The block schema of the program

In the program there are available two searching procedures: on the base of tomography images and decreasing of bone mass.
In procedure of searching on the basis of QCT, one can first read image – which will be analyzed, next to read images from data base. When sorting is ready, one should to insert number of image, which is the most similar, to the textbox of the program – the information about dangerous state will appear in the window of the program. This selected views of procedure box are presented in Fig. 28.
In procedure of searching on the basis of loss of bone mass one should indicate the proportional decreasing of bone mass (from the combo box) in each subregions of cortical bone in numerical model of pelvic bone. When all list are ready in the window of the program will appear information about dangerous state and potential dangerous of osteoporosis. This procedure was presented in Fig. 29.

6. Conclusions

- Applied procedure facilitates interpretation of data from QCT and it helps diagnosis what enable earlier detection of osteoporosis and enlarges chance of the treatment.
- Presented procedure delivers additional information about effort state in analyzed bone.
- Information from QCT can be helpful for researching progress of osteoporosis in individual clinical cases (because easier one can find the differences between earlier and later images).
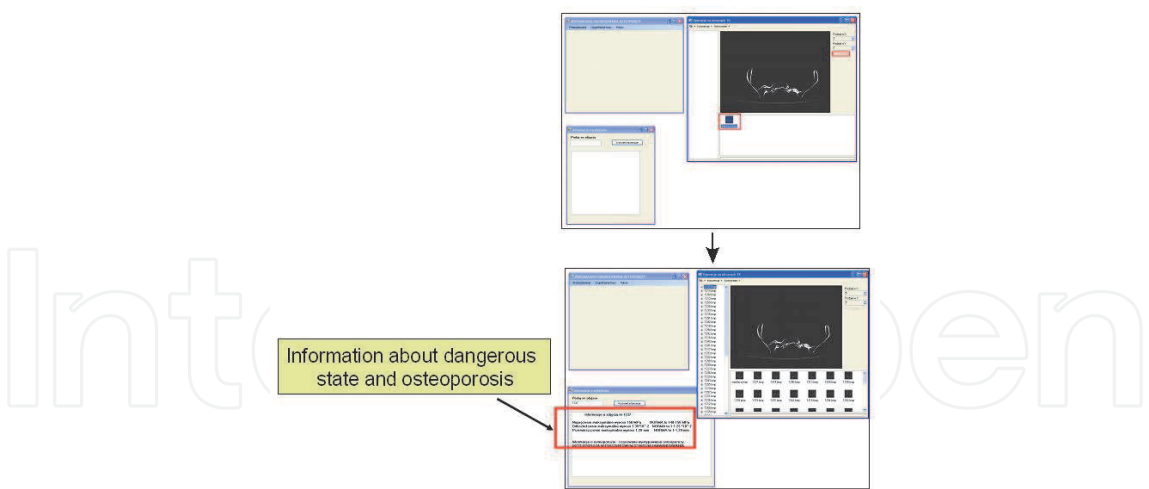
Fig. 28. The algorithm of the searching on the base QCT images

Fig. 29. The algorithm of the searching on the base loss of bone mass

- Subordinating individual images from QCT of effort state provides information about bone system.
- Creation of numerical model on the base of radiological data (especially material properties) increasing it conformance to real conditions.
- Quality of obtained results depends on amount information gathered in the data base.
- Presented procedure enables noticing changes in bones more precisely than standard methods (this is important when the difficulties with clear diagnosis appear).
- Structure of data base enables easy and quick extension.

7. Future plans

- Extension of data base. The structure of data base enables its easy extension. The more data collected in the base it means the bigger possibilities in aid of diagnosis.
- Widening this procedure to another element of bone system. Here, the example of pelvic bone was presented, but one can also applied this procedure to another bone and joint e.g. for the spine or metatarsus bone. To perform this one can dispose data necessary to prepare the numerical models and create proper data base.

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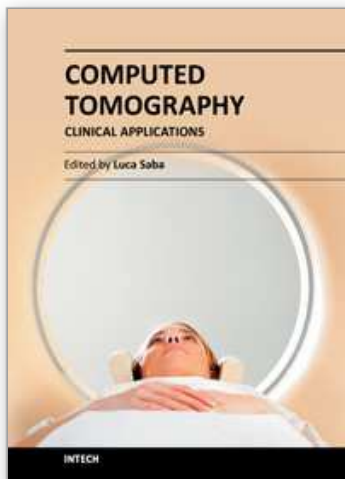
Computed Tomography - Clinical Applications

Edited by Dr. Luca Saba

Computed Tomography (CT), and in particular multi-detector-row computed tomography (MDCT), is a powerful non-invasive imaging tool with a number of advantages over the others non- invasive imaging techniques. CT has evolved into an indispensable imaging method in clinical routine. It was the first method to non-invasively acquire images of the inside of the human body that were not biased by superimposition of distinct anatomical structures. The first generation of CT scanners developed in the 1970s and numerous innovations have improved the utility and application field of the CT, such as the introduction of helical systems that allowed the development of the "volumetric CT" concept. In this book we want to explore the applications of CT from medical imaging to other fields like physics, archeology and computer aided diagnosis. Recently interesting technical, anthropomorphic, forensic and archeological as well as paleontological applications of computed tomography have been developed. These applications further strengthen the method as a generic diagnostic tool for non- destructive material testing and three-dimensional visualization beyond its medical use.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Antoni John and Piotr Wysota (2012). QCT as a Base of Computer Aided Diagnosis of Osteoporotical Changes, Computed Tomography - Clinical Applications, Dr. Luca Saba (Ed.), ISBN: 978-953-307-378-1, InTech, Available from: http://www.intechopen.com/books/computed-tomography-clinical-applications/qct-as-a-base-of-computer-aided-diagnosis-of-osteoporotical-changes

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