Analysis of bone formation and remodelling processes in the vertebra of cervical spine motion segment

Krzysztof Ścigała[1]

[1] *Division of Biomedical Engineering and Experimental Mechanics,*
Mechanical Engineering Faculty, Wrocław University of Technology,
ul. Łukasiewicza 7/9, 50-371 Wrocław, Poland
e-mail: krzysztof.scigala@pwr.wroc.pl

Abstract

The main aim presented analysis is estimation of formation process of trabecular structure in cancellous bone tissue of cervical spine vertebra. Two types of simulation were carried out. In first step distribution of bone density in the volume of cervical spine vertebra was estimated with application of classic model of bone remodelling proposed by Carter. Forces acting on vertebra was estimated for most often used basic movement in this part of spine. Basic, simply loading models were applied to selected motion segment model. Calculated displacement values were used as loading for model of single vertebra. Changes in bone density were calculated as a function of strain energy density and actual density in analysed point. In second step simulation based on trabecular remodelling algorithm proposed by Tsubota was used. Shape and composition of trabecular structures of cancellous bone were estimated as well as main load transfer mechanisms.

Keywords: computational biomechanics, bone remodelling, cervical spine

1. Introduction

Injuries of the cervical part of spine are the most often reasons of surgical treatment. However, in many cases negative results of degenerative processes in bone structures also leads to spine injuries and surgical operation. Degenerative processes are mostly results of cervical spine vertebra overloading or result of pathological process of load transfer. In case of significant changes in internal bone structure, proper treatment, specially with use of implants is difficult or impossible. Because of that estimation of architecture of trabecules inside in vertebra as well as estimation of bone mass distribution inside in vertebra is one of the most essential issues allowing understand vertebra biomechanics and optimisation of surgical technique.

Typical vertebra of cervical part of spine consist thin layer of compact bone tissue surrounding cancellous bone tissue, which is complex structures of so called trabecules – small rods of bone matrix. This structure plays significant role in load transfer process, however loads acting on the bone elements leads also to significant changes in bone mass distribution. Results of processes of bone remodelling exist on two levels. On the level of tissue changes in the bone density can lead to local overloading and initiation of bone fractures. On the level of bone tissue structure pathological structures of trabecules can lead to processes of damage accumulation in some parts of structure and formation of pathological tissue compounds.

Because of that development of numerical simulations allowing observation of remodelling processes on the level of tissue as well as on the level of tissue structure has significant role in the understanding of process of load transfer thru vertebra as well as influence of disturbances in this process on the damage development in the structure.

The main aim of presented analysis is estimation of formation and remodelling process in cancellous bone tissue of cervical spine vertebra by development of two types of numerical simulation: first one allowing observation on the bone tissue level, and second one allowing observation on the structure of bone tissue level.

2. Material and method

Geometrical models of vertebras were created using CT data form examination of real vertebras dissected form cadaver. Basing on typical x-rays of cervical spine and selected data from MRI examination was created model of intervertebral disc. Ligaments connected two vertebras was modelled using link elements. Position of attachments points for ligaments were found out also from MRI data.

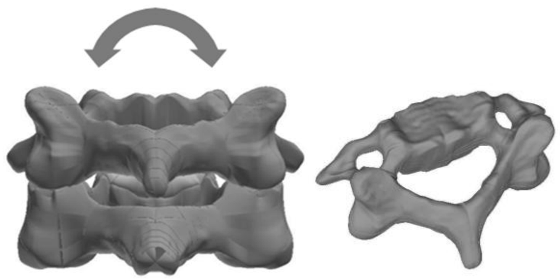

Figure 1: Geometrical model of cervical spine motion segment (a) and single vertebra (b)

Model of spinal motion segment were loaded using simplified loading models. Three most typical situations were described in loading models: bending in coronal plane, bending in sagittal plane and torsion. For each type of loading nodal displacements values were calculated and stored in additional file. Because of time of calculation, analysis of density distribution was carried out using model of single vertebra. Stored data of displacements values were transferred to the model of single vertebra and treated as initial loading. For each type of loading distributions of strain energy density were calculated. Mechanical stimulus of density change was calculated as a function of strain energy density, number of loading cycle for each type of loading and actual value of elasticity modulus. Calculation of changes of density were carried out iteration by iteration to the moment, when new density distribution was obtained [1], [3].

For calculations of trabecular changes two dimensional models of selected cross section in the model were used. Each area was filled with initial pattern of trabecules.

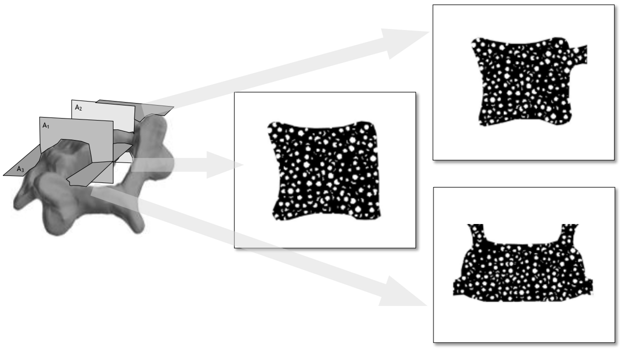

Figure 2: Position of analysed areas A_1, A_2, A_3, (a) and initial distribution of bone material in those areas(b)

Stimulus of remodelling was defined as proportional to the non-homogeneity in stress distribution on the surface of trabecules. Also in this case calculations of changes of density were carried out iteration by iteration [2], [4]

3. Results

Results of calculations of density distribution shows that in the vertebra body the highest values of bone density are obtained for the region located in upper anterior part of vertebra. It should be mentioned, so this regions located in the close range form pedicles connecting with vertebral arch.

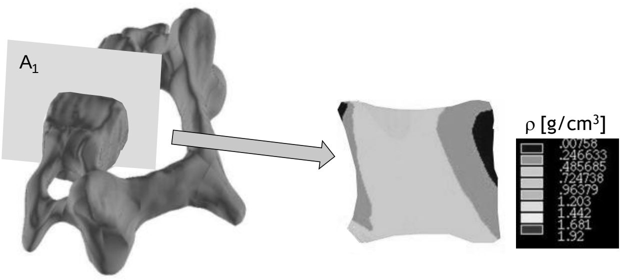

Figure 3: Position of analysed area A_1 (a) and bone density distribution (b)

Load transfer between two vertebras is realised not only thru intervertebral disc but also thru joint facets located in anterior part. Differences in the values of those forces leads to the bending of vertebral arch and increased level of stresses in region pedicles and in results also leads to increased values of bone density.

Results of investigations of trabecular structures show adaptation of internal bone architecture to the loading condition. In case of vertebral body we can observe so iteration by iteration bone structure becomes more directed. Vertical trabecules dominate in the structure, they are well developed with thickness significantly larger in anterior part than in posterior one. Some inclined trabecules are also visible, but they play mostly supportive role.

Combining of results from analysis of density distribution and analysis of trabecular formation allowed to estimate shape and distribution of basic load carrying structures. Main tracks of best developed trabecules should be described as: vertical trabecules in vertebral body, horizontal trabecules (lateral-medial direction) in the region of vertebral body endplates, and inclined trabecules in the pedicles.

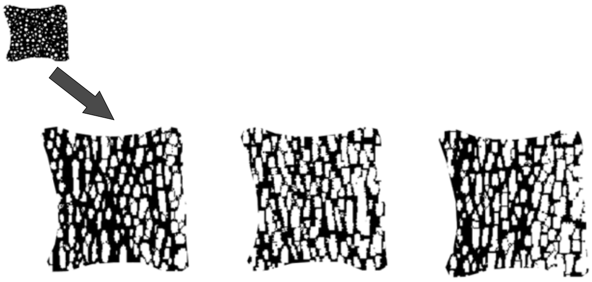

Figure 4: Formation of cancellous bone structures in one of analysed areas

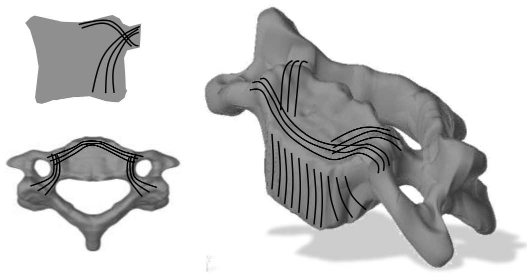

Figure 5: Basic structures of bone trabecules in cervical spine vertebra

Carried out analysis visualise distribution of bone structures in the vertebra volume. That kind of information is essential in treatment planning, especially in case of surgical techniques used in stabilization or intervertebral disc implantation.

References

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