Construction of individual geometric 3D model of the lumbar spine of a person based on the analysis of medical images

Tatyana Semenchenia
Sukhoi State Technical University of Gomel
Gomel, Belarus
levts@gstu.by

Konstantin Kurochka
Sukhoi State Technical University of Gomel
Gomel, Belarus
kurochka@gstu.by

***Abstract*—In this article, we will consider the algorithm on the basis of which an application was developed to build a three-dimensional model of the lumbar spine using images DICOM. The model is different from the existing ones so far as it has an intervertebral disk. The created application has been successfully tested.**

***Keywords*—computed tomography, DICOM, STL, 3D model, lumbar spine**

I. Introduction

The task of modern medicine is the study of pathogenic factors, as well as the identification of means to eliminate or weaken pathological processes. However, it seems obvious that in order to foresee the development and consequences of pathological processes, as well as to formulate medical recommendations, it is necessary to fully study both normal and impaired functioning of organs.

The numerical study of physiological and unnatural processes occurring in the human body is currently one of the most relevant and promising areas in scientific research.

Modeling and three-dimensional reconstruction are increasingly used as applied tools in various fields. Such areas include, in particular, medicine. Today, with the emergence of new diseases, it is increasingly difficult for doctors to make the correct diagnoses in the examination of patients, and when conducting high-precision surgery, it is necessary to have as much as possible a detailed idea of the state of internal organs. For example, it is often necessary to accurately construct a three – dimensional model of the human vertebra for the subsequent selection of the optimal implant design [1-3].

In many cases, to establish the diagnosis, the doctor visually examines the images of individual sections of the object obtained during the tomographic examination. However, for some clinical tasks, such as surgical planning, this is not enough [1].

The model provides much more information about the spine than can be obtained by modern measuring instruments.

Studies of the spine required for:

- analysis of the state of the spinal column, under unusual loads and pathological changes [4 – 6];
- choosing a reasonable method of correction [1];
- development of new correction methods [7];
- development of implant designs.

Pathological diseases and injuries are among the most common diseases of the human lumbar spine [8]. The number of diseases of the spine elements in humans is very large, and each case is individual, corresponding to a particular type of pathological changes or injuries [6].

Most of the pathologies of the spinal column are associated with osteochondrosis. It is this disease that most often leads to the progression of other disorders:

- intervertebral hernia;
- disc protrusion;
- sciatica;
- spinal cord compression;
- loss of sensitivity;
- spinal cord infarction.

Surgical treatment of the spine is performed to prevent compression of the spinal cord and the development of complications in osteochondrosis and intervertebral hernias.

Surgical treatment of diseases and injuries of the spine is carried out with surgical treatment:

- of osteochondrosis is used in the presence of the following complications: hernias and protrusions of the intervertebral discs, spondylolistea, secondary spinal stenosis.
- for traumatic lesions of the spine at all levels, including the consequences of spinal injuries and comprehensive treatment after “unsuccessful” previous operations.
- for cancer with damage to the spinal column, spinal cord, spinal roots.
- of a number of congenital anomalies of the spine.

Currently, the creation of three-dimensional models describing the lumbar spine of a person, and the study of these models will justify the methods of treatment of diseases or injuries, which determines the relevance of research.

Thus, the automation of the process of building a 3D model of the lumbar spine of a person is relevant. The significance is due to the fact that the development of materials and technologies for the production of prosthesis structures, implants, orthoses and other medical special technical means, as well as the combination of different methods of treatment requires research to confirm or refute this combination [9].

II. The main stages of building a three-dimensional model of the lumbar spine of a person

Currently, the treatment of diseases of the musculoskeletal system is impossible without the use and analysis of relevant biomedical images, a special place among which is occupied by the results of computed tomography, and, in particular, computed tomography of the human spine [10 – 13].

The result of computed tomography is a three-dimensional matrix of numbers representing the density of different parts of the object. The values of the matrix elements depend on the type of tissue under study and lie in a certain range, allowing to obtain three-dimensional images of the internal structures of the object under study [14].

Three-dimensional modeling allows to measure angles, lengths and diameters of different anatomical structures in the initial state and spatial transformations. This is essential in assessing the feasibility of reconstructive operations, in determining the most correct method of operation.

At design of a program complex it is possible to allocate several key stages of work (figure 1).

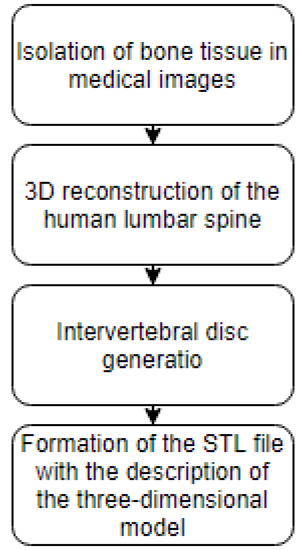

Figure 1. Key stages in the construction of a three-dimensional model of the lumbar spine of a person using computed tomography images.

The first step is the selection of bone tissue in medical images. This step will allow you to leave only significant information on the images.

The second stage is a three-dimensional reconstruction of the lumbar spine, as well as the generation of intervertebral discs.

The final stage is the formation of an STL file with a description of a three-dimensional model for further visualization and strength studies in CAD systems.

To perform the first stage of work, images were segmented [15], since the image elements corresponding to bone tissue in computed tomography images contrast sharply in comparison with other anatomical objects (figure 2), which is connected with the peculiarities of color representation in computed tomography image, which stores the value of the x-ray density of the captured object [16].

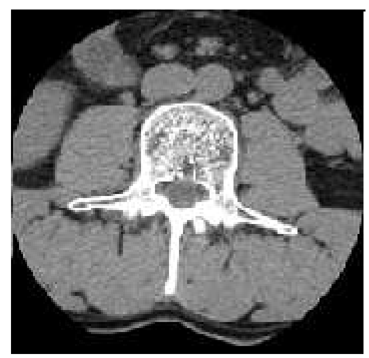

Figure 2. Sample image computed tomography.

To highlight the necessary areas in the images (bone tissue) for further processing and to eliminate noise in the form of a background, threshold transformations are used, such as:

$$T = T(x, y, p(x, y), f) \tag{1}$$

where f is an image; $p(x, y)$ is a local characteristic of the point (x, y) of the image.

The image $g(x, y)$ obtained as a result of the threshold transformation is determined by the formula:

$$\hat{g}(x, y) = \begin{cases} 1, & \text{if } f(x, y) \geq T; \\ 0, & \text{if } f(x, y) < T \end{cases} \tag{2}$$

where T is a threshold value; $f(x, y)$ is a pixel value; $g(x, y)$ is a value of the function that determines the belonging of the pixel to the object.

Thus, the pixels assigned the value 1 correspond to objects, and the pixels with value 0 correspond to the background [17].

Figure 3 shows the original images of spinal slices on computed tomography.

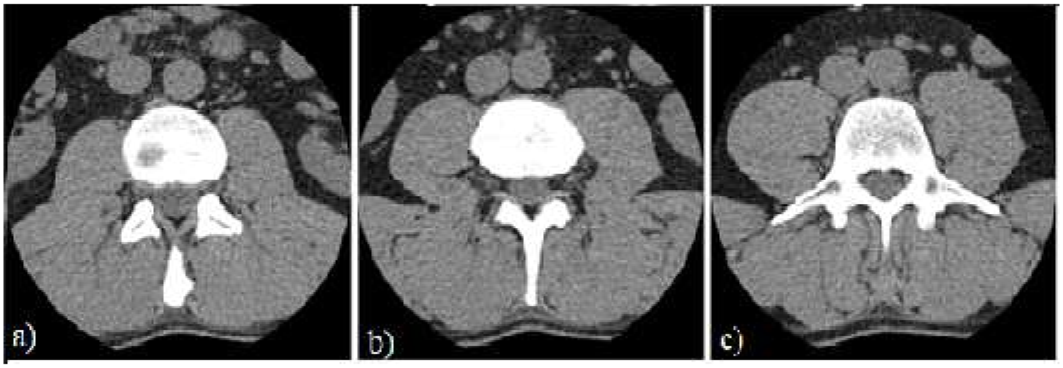

Figure 3. Image to threshold processing method.

After the threshold transformation of the image (figure 3 a, b, c) look as shown in figure 4 a, b and c, respectively.

Transformations allow the detection of bone tissue by selecting the optimal density (brightness) value, which is used as a threshold and allows you to distinguish the required objects from the background.

The image may be damaged by noise and interference of various origins. Averaging filters were used to suppress noise in the images. The idea of using averaging filters is to replace the original values of the image elements with the average values of the filter mask. This reduces the sharp transitions of brightness levels.

The use of averaging filters is to suppress "nonexistent" details in the image. By “nonexistent” we mean a set of pixels that are small compared to the size of the filter mask.

For visualization of the intervertebral disc, which is absent in the images of computed tomography, it was completed. At the first stage, images were found that lack a vertebral body (figure 5), and then images of the previous and subsequent vertebra with the body. The second stage was the reconstruction of the intervertebral disc.

An algorithm was written to restore the intervertebral disc, which consists of the following steps.

To obtain a clear contour of the objects in the processed image, the contour segmentation algorithm, the Laplace operator, is used. Using the Laplace operator [21] on each image, we find the contours of the spine, which in the vast majority of cases are closed curves. Figure 6 shows an example of the operation of the implemented algorithm.

The developed algorithm consists of the following steps:

a) the selected borders are viewed from top to bottom in layers (the layer in this case is the points that have the same y coordinate value);

b) if there is a distance between adjacent boundaries, then all layers already covered form a region and are recorded separately; at the same stage, after selecting the area, this area is divided, passing from left to right:

- the selected area is passed from left to right; if there is a gap between adjacent boundaries, then all layers that have already been covered will form a region and are recorded separately; if there is no clearance, then scanning continues until the region ends;
- if more than one contour was found in the new area being viewed, then they replace it;

c) if there is no clearance, then viewing continues until the layers being viewed are over.

The first stage is the recognition of the contour of the vertebral body in images that were detected earlier (the previous and subsequent vertebra with the body), as well as the formation of a list of points on the contours that are the coordinates of the triangle vertices.

The second step is to determine the contour with the least number of vertices. Figure 7 shows an example of two contours (upper contour and lower contour), where the upper contour is the required contour.

Next we connect the first point of the upper contour with the closest point of the lower contour. The remaining points are connected, as shown in figure 8.

As a result, you may get several cases:

- when the number of points on the contours coincides, then connect the vertices, as shown in figure 9, a.
- when the number of points on the contours differs by one, then connect the vertices, as shown in figure 9, b.
- when the number of points on the contours differs by two or more, then connect the vertices, as shown in figure 9, c.

For the three-dimensional reconstruction of the lumbar spine of a person the algorithm of triangulation of the surface «Marching cubes» was chosen as a basis [18]. The algorithm produces a partitioning of a region of space containing the surface of the cubic cell and approximarely the intersection of surface and every cubic cell. As a result, on the basis of the coordinates of

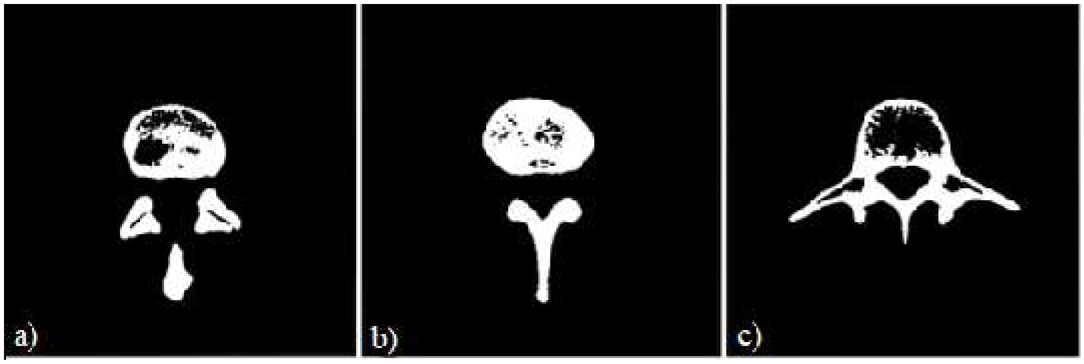

Figure 4. Image after threshold processing method.

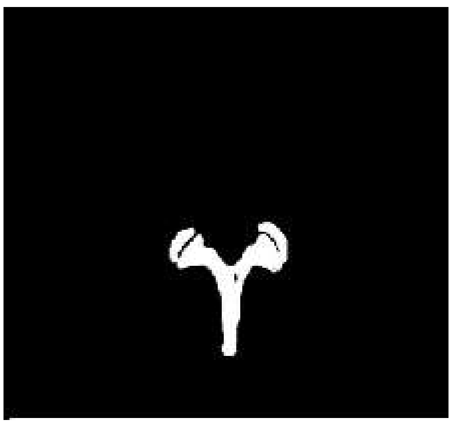

Figure 5. The image on which the vertebral body is missing.

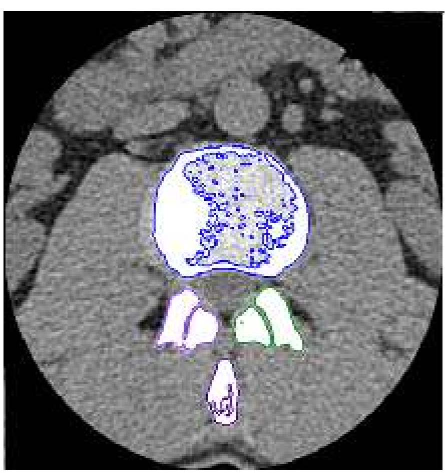

Figure 6. Isolation of individual sections of the vertebra, using the developed algorithm.

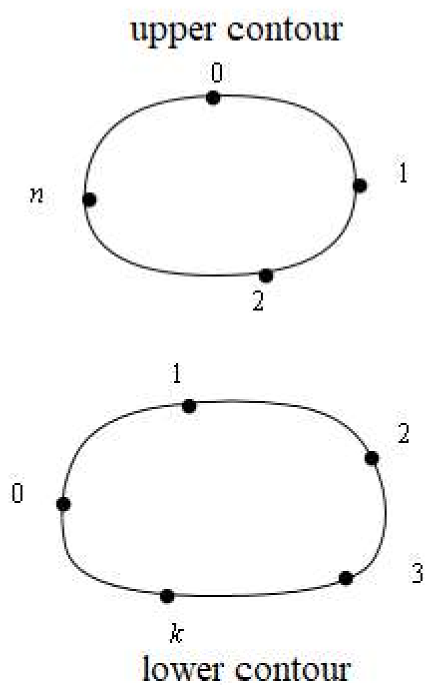

Figure 7. Contours of the vertebral bodies.

the points of bone tissue in the images of computed tomography, a list of the coordinates of the vertices of triangles that describe the three-dimensional surface, and the unit normals to them was formed.

Based on the obtained three-dimensional model of the lumbar spine of a person, an STL file is generated. Each resulting triangle is described by twelve 32 bit floating point numbers: three numbers for the normal and three numbers for each of the three vertices for the X/Y/Z coordinates.

III. Result

During the study, an algorithm was developed for constructing a 3D model of the lumbar spine of a person, which includes vertebrae and intervertebral discs, based on the analysis of DICOM images.

Figure 10 shows the result of visualization of a geometric 3D model of the human lumbar spine. The constructed computer models can be the basis for the development of the method of preoperative forecasting of

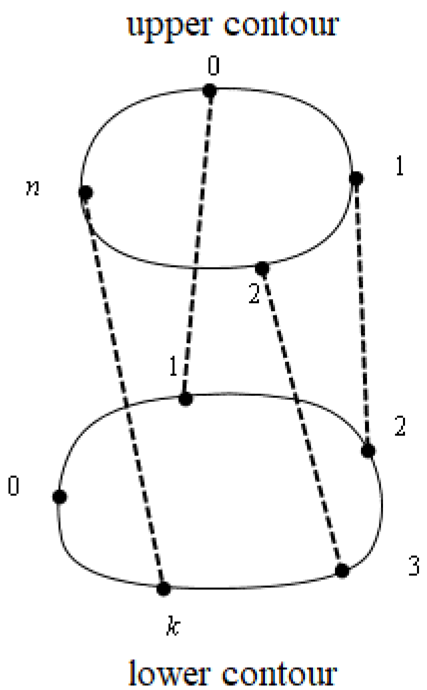

Figure 8. Connecting contour points.

the spine in various pathological formations, correction and prosthetics.

The developed software package for the construction of an individual geometric 3D model of the lumbar spine of a person based on the analysis of medical images differs from the existing possibility of building a three-dimensional model, which includes the vertebrae and intervertebral discs.

Also, the software package allows you to export models in STL format for further numerical experiments in computer-aided design systems aimed at obtaining information about the behavior of the lumbar spine of a person under the influence of various loads, as well as the impact on its stress-strain state of implants and other supporting devices.

Individual geometric 3D models of lumbar calving of the human spine can be used:

- to improve the assessment of spatial relationships of organs and structures;
- as a good example in the educational process (use of the model in the educational process for students and interns of neurosurgeons [1]);
- in scientific research (for example, studies to determine the risk of diseases of the musculoskeletal system [19]);
- to select the optimal fixing structure, options for attaching it to the vertebra;
- predict the effects of implantable elements (materials and structures that can replace the damaged item or some segment of the spine and to perform the functions assigned to the replaced element/segment) n the vertebral part of the patient;

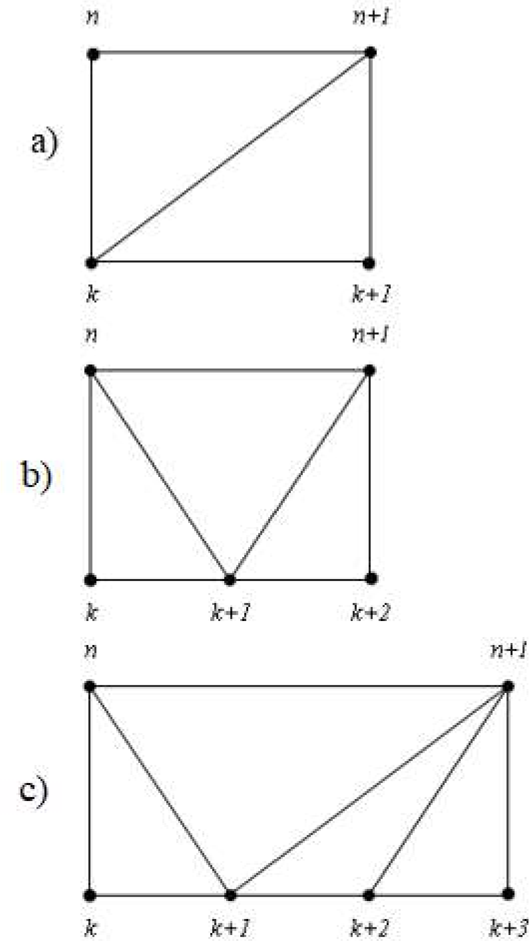

Figure 9. Vertex connection example.

- planning of some treatments (virtual simulation of radiation therapy, surgical navigation);
- assess the development of various diseases and pathologies [20] (for example, such as osteoporosis);
- to assess the normal and pathological anatomy of a particular patient, to predict surgical intervention, possible complications, and their prevention [2].

IV. Conclusion

As a result of the research, the program complex «Vertebra 3D» was developed, which has the following advantages:

1. possibility to build an individual geometric 3D model of the human lumbar spine, which includes vertebrae and intervertebral discs;

2. export of a three-dimensional model to the STL file format, which allows to directly materialize the

Figure 10. 3D model visualization.

reconstructed objects in the software complexes of three-dimensional modeling or complexes of finite element analysis, which allow to simulate the functional properties of the object and the implant, necessary to predict the impact of implantable elements or planning treatments;

3. the presence of means of visualization of the three-dimensional model;

4. cross-platform operation of the software package.

The use of the developed software package for constructing an individual geometric 3D model of the lumbar spine of a person contributes to the optimization of the work of medical personnel, reducing the load on medical workers and reducing the impact of the human factor on the accuracy of the results obtained in the analysis of the spine, anatomical studies of vertebral segments or the development of implant design.

References

[1] M. V. Olizarovich, Computer modeling of the lumbar vertebrae in the preoperative period, Health and ecology problems, 2013, no. 12, p. 125-129.

[2] O. N. Yamshchikov, Computer modeling in traumatology and orthopedics, TSU Bulletin, 2014, no. 6, p. 1974-1979.

[3] M. P. Burykh and R. S. Voroshchuk, Voxel anatomical modeling of human internal organs, Clinical Anatomy and Operative Surgery, 2006, no. 5, p. 115-118.

[4] V. P. Balandin and V. S. Tuktamyshev, Computer simulation of the effect of intra-abdominal pressure on the loading of the spinal column, Master's journal, 2015, no. 2, p. 229-237.

[5] N. Kh. Tsurova, Biomechanical research and modeling of the lumbar spine segment, News SPEBGTU "Lati", 2008, no. 3, p. 73-78.

[6] N. Kh. Zinnatova, Biomechanical method for diagnosing the state of the spine in health and pathology, Proceedings of the Southern Federal University. Technical science, 2009, p. 108-113.

[7] S. V. Orlov, R. L. Sedov and N. D. Bobarykin, Mathematical modeling of spinal instability and stabilization methods, Russian Journal of Biomechanics, 2010, no. 3, p. 36-46.

[8] P. V. Netsvetov, A. T. Khudyaev and G. V. Dyachkova, X-ray characterization of fractures of the thoracic and lumbar spine, according to computed tomography, at various stages of treatment with the method of transpedicular fixation, Genius Orthopedics, 2007, no. 1, p. 69-75.

[9] O. V. Veretelnik, N. A. Tkachuk and I. B. Timchenko, Mathematical and numerical study of various designs of orthoses for cervical spinal spondylode, Bulletin of the National Technical University "KPI", 2017, no. 29, p. 27-37.

[10] A. N. Chuyko, An approximate analysis of the anatomy, mechanical characteristics and stress-strain state of the human spine, Injury, 2014, vol. 15, no. 6, p. 100-109.

[11] A. M. Zharnov and O. A. Zharnova, Biomechanical processes in the vertebral motor segment of the cervical spine during its movement, Russian Journal of Biomechanics, 2014, vol. 18, no. 1, p. 105-118.

[12] K. S. Kurachka and I. M. Tsalka, Vertebrae detection in X-Ray images based on deep convolutional neural networks, INFORMATICS 2017: Proceeding of the 2017 IEEE 14th International Scientific Conference on Informatics, Slovakia, 2017, pp. 194-196.

[13] K. S. Kurachka, V. V. Komrakov and N. N. Masalitina, The automated classification system for lumbar spine anatomic elements, Nonlinear Dynamics and Applications, 2017, vol. 23, p. 127-134.

[14] M. Ya. Marusina and A. O. Kaznacheyeva, Modern types of tomography. Tutorial, SPb: SPbSU ITMO, 2006.

[15] Yu. A. Ogluzdina, Image segmentation algorithms, Youth Scientific and Technical Gazette, 2014, no. 8, p. 11-17.

[16] E. V. Doronicheva and S. Z. Savin, Medical image recognition methods for computer-aided diagnostic tasks, Modern problems of science and education, 2014, no. 4, p. 30-38.

[17] R. Gosales and R. Woods, Digital image processing, Moscow: Technosphere, 2005.

[18] W. E. Lorensen and H. E. Cline, Marching Cubes: A high resolution 3D surface construction algorithm, SIGGRAPH, 1987, vol. 21, no. 4, p. 163-169.

[19] E. L. Tsitko, K. S.Kurochka, N. N. Masalitina, I. N. Tsalko, I. N. Komrakov and E. V. Tsitko, The radiometric estimation of kinematics of the lumbosacral spine segments of osteochondrosis with the help of the software «Volot», Health and ecology problems, 2017, no. 4, p. 35-41.

[20] A. Yu. Mushkin, E. V. Ulrich and I. V. Zuev, Spine biomechanics in health and pathological conditions: the main aspects of research, Spinal surgery, 2009, no. 4, p. 53-61.

[21] W. Pratt, Digital image processing, M.: Mir, 1982.

Построение индивидуальной геометрической 3D модели поясничного отдела позвоночника человека на основе анализа КТ-изображений

Семенченя Т.С., Курочка К.С.

Предложен алгоритм, позволяющий по результатам компьютерной томографии поясничного отдела позвоночника человека, представленной в виде DICOM-файлов, сформировать трёхмерную модель, отличающуюся от существующих сгенерированным межпозвоночным диском. На основе алгоритма создано соответствующее программное обеспечение и проведена его аппробация.

Received 15.01.2020