Extraction of Vertebrae from CT Images

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Abstract: *The algorithm of extraction and separation of vertebrae from collections of CT images is presented. For this purpose so-called topograms are used. The topogram image is a 2D image of whole patient body made from above. The algorithm finds automatically the spinal [vertebral] column and then separates vertebrae. It is designated for automatic and semi-automatic separation and counting vertebrae on collections of 2D CT images.*

***Keywords*:** Medical image segmentation, CT images, spinal column, vertebrae.

1. INTRODUCTION

There is no need to explain important role of medical imaging in current human life. One of its actual and important problems is the task of extraction spine column and vertebrae from MR and CT images. Evidently, results of solution of this task are useful for medical specialists studying or treating spinal deceases as well as for experts making diagnoses of alteration other internal organs (kidney, the liver, lungs etc.) .

Now tasks of determining spine column, separation and counting of vertebrae on CT images are usually carried out by medical specialists manually. This routing work takes significant time and effort of experts. Algorithms, which solve or even partly solve mentioned problems, seriously facilitate the work with CT datasets having from several dozen to hundreds images. A dataset of CT images of a patient is stored as 2D grayscale scans of body axial section (Fig.2) written in the DICOM format. It usually contains the topogram image, which is a 2D image of whole patient body made from above (Fig.1).

Fig.1 – Example of CT topogram.

Medical experts very often need localization of parts of human body and human organs shown in 2D scans. For this purpose numbering of vertebrae is traditionally used. To find a vertebra number the expert should seek correspondence between the current 2D scan image and its approximate position in topogram, which depicts the entire human body in the orthogonal direction (Fig.1), and then find the number of vertebra shown in the scan. It is rather routine and time consuming manual operation. Some modern tomographs have special options to show regions of CT images in the topogram and vice versa, but as a rule they do not save such type information in files.

Now several approaches to automatic extraction of spine column and vertebrae are known [1-6]. They depend essentially on resolution of the CT scanner. High resolution of CT scanners allows use of modal based techniques but in general case it is not so easy since distance between 2D tomographic scans can be too large, for instance, 1cm or more.

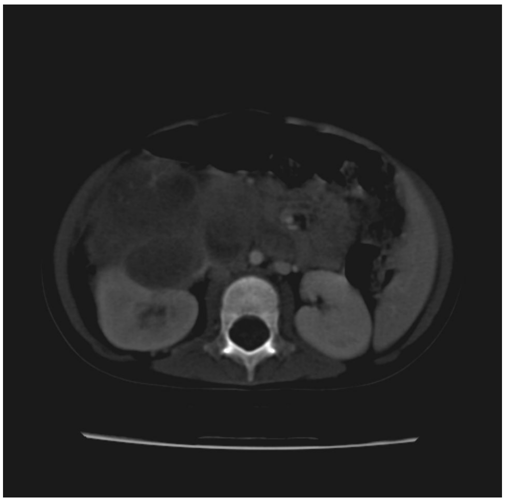

Fig.2 – Example of 2D CT image of human body.

We offer an approach to extraction of spine columns from CT images and separation of vertebrae. It enables automatic segmentation of spine column region and automatic or semiautomatic separation of vertebrae. We offer our solution in the traditional decision making form as a prompt for the medical expert who can easily correct the result of automatic separation of vertebrae in the topogram in order to fix numbers of vertebrae shown in 2D tomographic scans.

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2. FORMULATION OF PROBLEM

Usually a dataset of CT images of one patient consists of 20÷100 scans (Fig.2) accompanied with the topogram (Fig.1). Distance between scans can vary from 0.1 to 1 centimeter. All images are stored as files in the DICOM format. Each DICOM file contains 3D coordinates of the top left corner of the 2D scan image relative to the coordinate system of the CT scanner.

One of difficulties for experts to work with the CT dataset consists in absence of interconnection of successive numbers of files and their real 3D coordinates. A CT scan can have arbitrary Z-coordinate relative to the human body Therefore, 2D scans should be ordered in regard to their space disposition before one begins to segment human organs.

DICOM pictures are represented as 16-bit grayscale images. Brightness of DICOM images of 2D CT scans corresponds to the Hounsfield units that characterize organ densities. Unfortunately, it is not referred to topograms. An appropriate transformation of DICOM images, especially topograms, into the standard 8-bit gray scale ones can help to get maximum accuracy of further steps.

So, ***initial data*** for our task is datasets of 2D tomographic scans of 1-18 years old children. Each dataset is accompanied with the topogram. All images are provided with their 3D coordinates according to the coordinate system of the CT scanner.

Our task is to estimate position of vertebrae in the topogram and the number of the vertebra shown in a 2D scan.

The main steps of the offered decision rely on finding characteristic bright spots on the spine column of forms either oval or line segments (Fig.1). Those bright segments are formed by specificity of vertebrae form. In the sequel they will be called ***spots***.

3. DESCRIPTION OF ALGORITHM

Before use of CT images they are transformed into the 8-bit grayscale format with accurate correction of their color, since originally the pictures are very soft. The histogram stretching gives here better results in comparison with the equalization. Also sharpening of the contrast can be used.

The topogram is slightly smoothed by the windowed 2×2 averaging filter.

Each DICOM file of the CT dataset contains 3D coordinates of the image in accordance with the coordinate system OXYZ of the scanner. Space position of images plays important role for the offered approach. 2D scans of human body are orthogonal to Z-axes of the coordinate system OXYZ, and topogram is contrariwise parallel to this ray. The images are usually unordered, so we sort them in regard to their Z-coordinate. In the following only ordered 2D scans are exploited.

As it was mentioned above, the distance between neighbouring 2D scans can be rather large so that the question whether those two adjacent scans contain images of same vertebra and ribs or not is very hard.

In our previous work we successfully extracted vertebrae from 2D scans based on the Hounsfield scale and the modal based search [7]. Therefore, one of the simplest ways to extract the spine column and vertebrae was thought as segmentation of vertebrae in 2D scans and finding corresponding regions in the topogram based on space coordinates of images. But it turned out a position of the spine column in the scans significantly differs from its position in the topogram because of movements of the patient body during the long time scanning procedure.

These two facts compelled us to use for ***our task*** namely topograms that represent more or less continuous pictures of fixed human bodies.

From the first look it seems the spine column separates the human body into two symmetric parts. However, this hypothesis is almost always not correct. Three different algorithms were applied to find the spine column center. The most precise estimate of the spine center gave quadratic regression that approximated centers of horizontal lines crossing body in the topogram image (without the upper extremities) from one its side to the other.

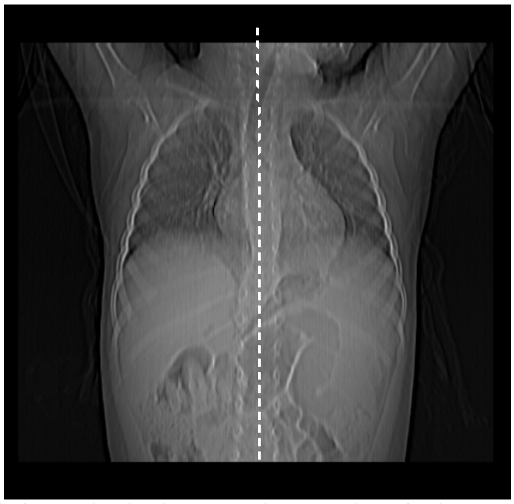

Fig.3 – White line is quadratic regression of spine centre

Some notations are needed to describe in details next steps. Let $S=\{0,...,n-1\}\times\{0,...,n-1\}$ be the set of pixels $\mathbf{p}=(j_1,j_2)\in S$, and $\mathbf{I}$ be a $n\times n$ grayscale image with brightness values $I_{\mathbf{p}}\in\{0,...,255\}$. Denote by $W_{l,m}(\mathbf{p})$ the symmetrical $l\times m$ rectangle region of pixels $W_{l,m}(\mathbf{p})\subset S$ with the center pixel $\mathbf{p}$ and let

$$\Delta_1(\mathbf{p})=I_{(j_1-1,j_2)}-2I_{(j_1,j_2)}+I_{(j_1+1,j_2)},$$
$$\Delta_2(\mathbf{p})=I_{(j_1,j_2-1)}-2I_{(j_1,j_2)}+I_{(j_1,j_2+1)}$$

be numerical derivatives of the second order. Denote also

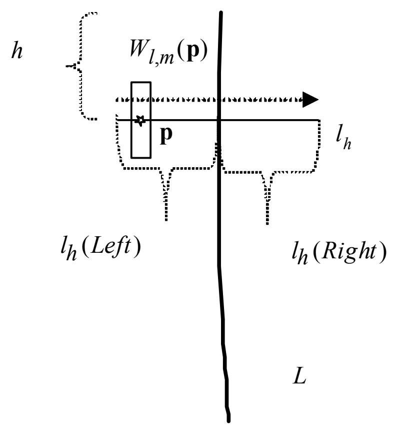

Fig.4 – Diagram of computation of function $g_h(\mathbf{p})$.

by l_h horizontal line segment of the length $|l|$ that intersects symmetrically (we mean $l_h(Left)=l_h(Right)$) the center line L of the spine column at the height

h (Fig.4).

To find visible traces of *spots of vertebrae* the following procedure is developed. For each value h of Y-coordinate of the topogram (Fig.4), each pixel $\mathbf{p}$ belonging to the segment l_h and the thin rectangle window $W_{l,m}(\mathbf{p})$ of some fixed size (in our case $l=2, m=12$) values of the function

$$g_h(\mathbf{p}) = \sum_{\tilde{\mathbf{p}} \in W_{l,m}(\mathbf{p})} \left(|\Delta_1(\tilde{\mathbf{p}})| + |\Delta_2(\tilde{\mathbf{p}})| \right) \qquad (1)$$

are computed. After the maximum value of every function $g_h(\mathbf{p})$ over the segments l_h are determined

$$G(h) = \max_{\mathbf{p} \in l_h} g_h(\mathbf{p}) . \qquad (2)$$

It can be seen that deep local maxima of the function $G(h)$ with high probability correspond the case when the segment l_h intersects a bright spot formed by transverse process of vertebrae (Fig.5). The function $G(h)$ is used

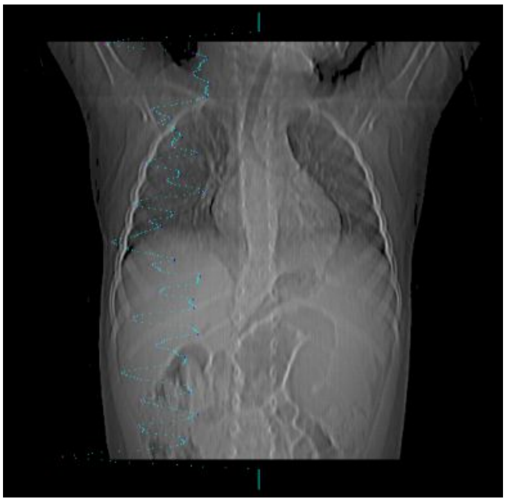

Fig.5 – Value of function $G(h)$ is shown with turquoise color

for the next step of the algorithm to estimate position of spine column boundaries. It also could be applied to vertebra extraction but it would give less precise results. Local maxima of $G(h)$ are determined via approximation of this function by broken line functions in the ℓ_∞ space with the norm $\|G\|_\infty = \max_h |G(h)|$ [8,9]. After the maxima are found, for instance, at heights $h_1, h_2, ..., h_k$ the brightest regions of the second order derivative of the smoothed topogram at these heights are estimated with the help of functions

$$\mathbf{p}_{j,Left} = \arg\max_{\mathbf{p} \in l_{h_j}(Left)} g_{h_j}(\mathbf{p}), \qquad (3)$$

$$\mathbf{p}_{j,Right} = \arg\max_{\mathbf{p} \in l_{h_j}(Right)} g_{h_j}(\mathbf{p}), \qquad (4)$$

where $l_h(Left)$ and $l_h(Right)$ are left and right parts of the line segment $l_h = l_h(Left) \cup l_h(Right)$ as shown in Fig.4. The estimates of left and right boundaries of the spine column are built as square regressive lines L_{Left} and L_{Right} approximating points $\mathbf{p}_{j,Left}$ and $\mathbf{p}_{j,Right}$ respectively (Fig.6).

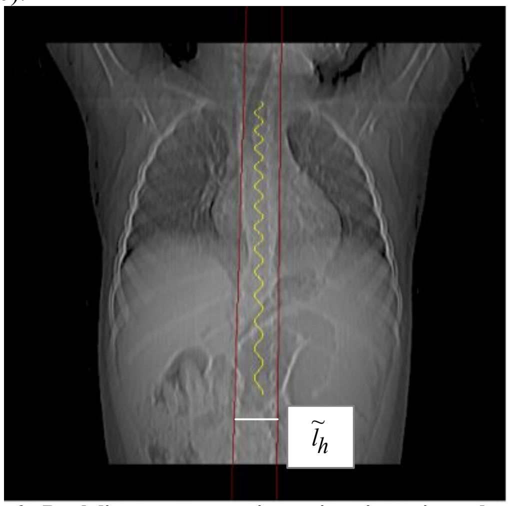

Fig.6 – Dark lines are regression estimating spine column.

Now we compute more accurate estimator of vertebrae with the help of the function

$$V(h) = \max_{\mathbf{p} \in \tilde{l}_h} \sum_{\tilde{\mathbf{p}} \in W_{l,m}(\mathbf{p})} \left(\mathbf{1}_{\{|\Delta_1(\tilde{\mathbf{p}})| \geq \tau\}} + \mathbf{1}_{\{|\Delta_2(\tilde{\mathbf{p}})| \geq \tau\}} \right), \qquad (5)$$

where the horizontal line segments $\tilde{l}_h$ join estimated boundaries L_{Left} and L_{Right} of the spine column (Fig.6), the function $\mathbf{1}_A$ is the indicator of the set A, the number τ is an appropriate threshold.

To estimate the characteristic bright spots of transverse process of vertebrae we approximate the function $V(h)$ by the cosine. Immediate approximation of $V(h)$ is rather promising but it does not give the best result. To improve the approximation we first compute

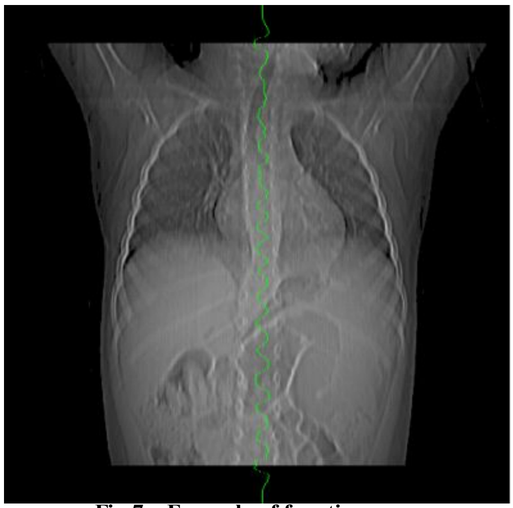

Fig.7 – Example of function $R(h)$.

the low frequency component of $V(h)$ by averaging of the function via the moving average filter.

Then the low frequency component $\tilde{V}(h)$ is discriminated from $V(h)$, i.e. instead of this function the difference

$$U(h) = V(h) - \widetilde{V}(h) \qquad (6)$$

is used. Before approximation of $U(h)$ we equalize its amplitudes by the transformation

$$R(h) = sign(U(h))\sqrt{|U(h)|}\ . \qquad (7)$$

The example of the function $R(h)$ is depicted in Fig.7. At middle heights $R(h)$ looks as a trigonometric function. Therefore, to estimate disposition of the characteristic vertebrae spots we approximate the function $R(h)$ by the cosine with a variable period. The approximating function is taken of the form

$$f_{\alpha,\beta,\lambda,\mu}(h) = \alpha \cos((1+\beta h)\lambda h + \mu) \qquad (8)$$

with regressors $\alpha, \beta, \lambda, \mu$. The solution is found as

$$\widetilde{\alpha}, \widetilde{\beta}, \widetilde{\lambda}, \widetilde{\mu} = \underset{\alpha,\beta,\lambda,\mu}{\arg\min}\left(\sum_{h=k}^{K}(R(h) - f(h))^2\right) \qquad (9)$$

for integer numbers k and K corresponding the bottom and the top of the body image in the topogram.

Maxima of the regression function $f_{\widetilde{\alpha},\widetilde{\beta},\widetilde{\lambda},\widetilde{\mu}}(h)$ on its argument h evaluate positions of *spots* of vertebrae.

Describe in brief the detailed flow chart of the approach.

Step1. (Preliminary). Read 3D coordinates of CT images stored in the DICOM format and sort them according to their real position in the space.

Step2. (Preliminary). Transform CT images into the 8-bit grayscale format with stretching their histograms and smoothing pictures by the windowed averaging filter.

Step3. (Finding spine column boundaries I). Compute functions $g_h(\mathbf{p})$ and $G(h)$ according to formulae (1), (2). (Fig.5).

Step4. (Finding spine column boundaries II). Approximate $G(h)$ by the broken line function in ℓ_∞ space.

Step5. (Finding spine column boundaries III). Find deep maxima of $G(h)$ with the help of the approximating broken line function.

Step6. (Finding spine column boundaries IV). Determine preliminary estimates of 2D coordinates of left and right *spots* of vertebrae $\mathbf{p}_{j,Left}$ and $\mathbf{p}_{j,Right}$ by formulae (3), (4).

Step7. (Finding spine column boundaries VI). Compute square regressive lines L_{Left} and L_{Right} that approximate points $\mathbf{p}_{j,Left}$ and $\mathbf{p}_{j,Right}$ respectively. (Fig.6).

Step8. (Estimation of spots of vertebrae I). Compute function $V(h)$ – more accurate estimator of *spots* of vertebrae by (5).

Step9. (Estimation of spots of vertebrae II). Discriminate from function $V(h)$ low frequencies by windowed averaging filter (6) and equalize it by (7) to use instead of $V(h)$ function $R(h)$.(Fig.7).

Step10. (Estimation of spots of vertebrae III). Approximate $R(h)$ by the periodic function $f_{\alpha,\beta,\lambda,\mu}(h)$ by (9).

Step11. (Estimation of spots of vertebrae IV). Find maxima of $f_{\widetilde{\alpha},\widetilde{\beta},\widetilde{\lambda},\widetilde{\mu}}(h)$ on h and use them as estimates of heights of transverse vertebra processes.

2. EXPEREMENTS

The approach was programmed in the C#.Net programming language.

The datasets of 29 CT image collections of children of age $1 \div 18$ were processed. The applied task was to separate correctly vertebrae of thorax since many human organs including kidney are disposed inside it. Vertebrae of 27 datasets were separated 100% correctly. In 1 case 1-2 top vertebra were separated incorrectly due to defect of the spine column. The other topogram contained two very contrast round markers that caused error separation of 2 vertebrae. So, the rate of correctly separated thoracic vertebrae was more that 90%. An Example of correct separation of vertebrae is shown in Fig.8. The dark horizontal line segments pass through *spots* of vertebrae. Bright line represents of the graph of the regression function $f_{\widetilde{\alpha},\widetilde{\beta},\widetilde{\lambda},\widetilde{\mu}}(h)$.

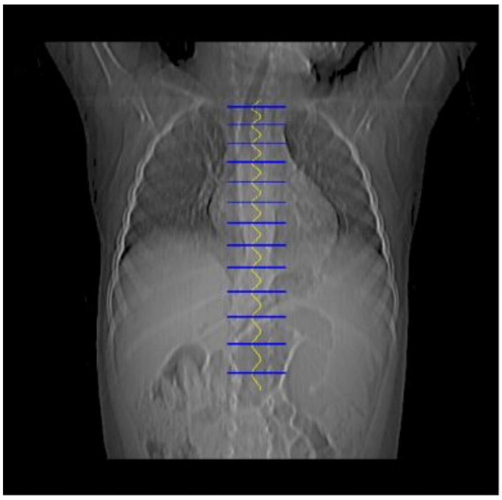

Fig.8 – Example of correctly separated vertebrae.

We guess the algorithm should be specially trained to separate cervical vertebra in topograms, since images of those vertebrae differ in form and size from images of thoracic ones.

Separation of lumbar and sacral vertebrae is not so easy problem because they can be even invisible in CT topograms.

In order to avoid minor number of possible errors and allow medical expert more confident processing of CT datasets we offer in addition the interactive mode of manual correction of vertebrae separation. The expert can manually shift separating line segment, take away or add new lines.

After the final separation of thoracic vertebrae in the topogram was done the expert can number them. For that the bottom vertebra with ribs can be found (usually it is 12th thoracic vertebra) and numbers of other vertebrae are assigned relatively to it.

Usually medical experts need to know a number of the vertebra he sees in the 2D CT scan image since disposition of internal organs is fixed not in metric units but with the help of vertebra numbers. After the final vertebra separation procedure numbers of thoracic vertebra under review become available at any moment of time.

5. CONCLUSION

The presented algorithm allows automatic and semiautomatic extraction of the spine column and thoracic vertebrae from datasets of CT images stored in the medical DICOM format. It enables of reliable extraction and separation of thoracic vertebrae in order to number them relative to the bottom human vertebra with ribs (usually it is 12th thoracic vertebra).

In turn, it gives possibility for the medical expert to know the number of the vertebra he sees in the current 2D scan image.

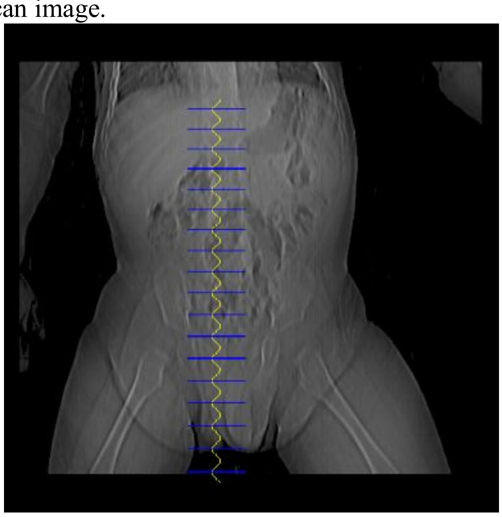

Fig.9 – Example of invisible sacral vertebrae.

The drawback of the algorithm is its real applicability to separate and number only thoracic but not lumbar and sacral vertebrae.

In the future we are going to study possibility of reliable automatic determining of the bottom vertebra with ribs.

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