The study presented an approach to the morphometric image of atherosclerotic lesions of the final segment of the abdominal aorta, femoral and iliac arteries, considering possible endovascular intervention. The evaluation of these arteries is very important, because they are often used as a point of access for endovascular procedures performed on the peripheral arteries, or within the thoracic and abdominal aorta and its branches, as well as coronary arteries.

The aim of the study was to determine morphometric measurements describing the atherosclerotic lesions, including the methodology of their surgical interpretation.

Material and methods. The study group comprised 128 tomograms of patients qualified for surgery. An algorithm based on the mathematical morphology was designed to track the vessels, starting from the division of the common femoral artery, and ending at the bifurcation of the abdominal aorta. We proposed a set of numerical measurements of the observed arterial changes.

Results and conclusions. We analysed 128 tomograms with a 94.5% efficiency, and with the assessment accuracy of the degree of lumen reduction (MAE - 1.5%). We observed much higher measurement values of local tortuosity of the atherosclerotic arteries (0.3 – 1 radians), as compared to their anatomical course in a healthy subject (0 – 0.2 radians). The presented method can be a very accurate and useful tool in the numerical analysis of the lumen distribution of the arteries and atherosclerosis, dedicated to surgeons elaborating management strategies.

Key words: atherosclerosis, femoral artery, iliac artery, endovascular intervention, computed tomography, image analysis

The numerous methods currently used in vascular diagnostics are concentrated on detecting and determining the degree of arterial stenosis, directing surgical or endovascular management towards the restoration of normal blood flow (1, 2). The commonly performed “Doppler examinations”, classical angiography, or computed tomography demonstrate focal or multiple stenotic lesions, which might be directly responsible for lower limb ischemia. The use of arterial visualization during angiography or computed tomography often helps determine the degree of arterial blood flow at a given moment, its course, location of atherosclerotic plaques, and resulting relevant information concerning surgical management (3). The implementation of the latest technological solutions led to the rapid development of endovascular methods (4, 5, 6). Especially for this reason the assessment of the femoral and iliac arteries is extremely important, because the above-mentioned are most commonly used, considering access to endovascular procedures of the peripheral arteries, as well as thoracic
and abdominal aorta and its branches, and coronary arteries (7, 8, 9).

The presented study mainly focused on imaging diagnostics of atherosclerotic lesions of the distal segment of the abdominal aorta, as well as iliac and common femoral arteries. One should keep in mind that imaging methods only support the diagnostic process, where the physical examination and medical history remain most important. Their interpretation gives us information on the location and severity of atherosclerotic lesions, considering the anatomy and topography of the vessels (10, 11). These aspects in the evaluation of the vascular bed are extremely important, because they allow to precisely determine the location of atherosclerotic lesions, and plan treatment by means of different techniques: classical surgery, endovascular intervention, and hybrid surgery.

The aim of the study was to determine morphometric measurements describing the atherosclerotic lesions, including the methodology of their surgical interpretation.

**MATERIAL AND METHODS**

The study group comprised 128 tomograms of patients qualified for surgical intervention with different intensification of atherosclerotic lesions. 512 arterial segments were evaluated (common iliac, external iliac, internal iliac, and common femoral). Average patient age was 65 years (ranging between 40 and 86 years). The study analysis was performed between 2006 and 2010. Only arteries with continuous flow were subjected to numerical analysis. All patients were examined at the Military Institute of Medicine using a 64-row CT, manufactured by General Electrics (Fairfield, CT, USA). Tomography images had a 512x512 pixel resolution, and were stored in DICOM ver. 3 format. For each of the analysed iliac and femoral artery segments there were 220 to 320 tomography radiograms.

In order to perform computer analysis of the analysed arterial segments a mathematical algorithm was established, designed to track vessels, starting from the division of the common femoral artery and ending at the bifurcation of the abdominal aorta. Automatic computer analysis of consecutive images, considering the MSCT sequence is performed using the method of enhanced local maxima and filtration by means of morphological advances (12). The result of the above-mentioned in the form of a binary mask contains both, arterial sections and that of smaller vessels and bones. Therefore, the need for the selection of proper objects corresponding to the analysed arteries. Thus, the need for the morphological reconstruction of objects, their position corresponding (overlapping) the cross-sections of the arteries isolated from the previous MSCT sequence scans. During each step of tracking the arteries the isolated arterial surfaces are also segmented into the vascular lumen and atherosclerotic plaques, according to the methodology described in the study. Fig. 1 presented the methodological scheme of arterial tracking.

In order to recognize the cross-section areas of the vascular lumen with preserved blood flow continuity and calcified atherosclerotic plaques, the threshold strategy was used, based on mixed Gaussian models and statistical measures.

To describe the numerical severity of atherosclerotic lesions a set of morphometric features was proposed. The basic measure is the degree of vascular lumen stenosis defined as the ratio of the surface of the plaques to the total cross-section of the vessel (total area of the surface of the vascular lumen and plaques). Another measure is the reduction of the vascular lumen surface in relation to the ellipse surface of the described cross-section. The above-mentioned is considered as the approximation of the primary surface of the vascular lumen, which was limited not only by the calcified plaques, but also by non-calcified plaques which are difficult to detect. In order to define the described ellipse the shortest and longest axis of the vascular surface were used. The distribution of plaques on the internal surface of the vascular wall and degree of lumen stenosis were also estimated numerically. Figure 2 presented these results. In addition to the diameter, arterial blood flow, and spatial distribution of atherosclerotic plaques, the tortuosity of the arteries is also a very important issue, especially in case of the iliac vessels. This is closely associated with the possibility to introduce tools and systems used during endovascular procedures.

The direction of the vessel can be described as a vector connecting the central points of its cross-sections in consecutive CT images. The
direction was determined by the simple approximation of different points, the so-called spatial vector. The change in the direction of the artery was calculated as the change in the angle between successive spatial vectors (3D). The determination of the above-mentioned was based on 10 consecutive images. The measure of the directional volatility might be important not only in case of demonstrating the so-called „acute angular flexion“, but also in case of the general evaluation of the numerical degree of vascular tortuosity.

RESULTS

The proposed methodology and elaborated computer algorithms allowed to carry out analysis of the clinical material. Considering the study database (128 patients) the above-

Fig. 1. General scheme of the algorithm evaluating the course of the arteries in CT sequence scans

Fig. 2. Illustration and spatial evaluation of atherosclerotic plaques located unilaterally (a) and the entire vascular wall diameter (b)
mentioned was characterized by the following specific cases:

- 13 patients with only right-sided flow,
- 12 patients with only left-sided flow,
- 2 patients without flow in both arteries,
- 3 patients were not suitable for analysis (low signal to noise ratio),
- 3 patients required manual intervention when determining arterial cross-section points by means of MSCT sequence scans,
- 2 patients with problems preventing automatic evaluation.

As a result, seven patients had to be excluded from the study (algorithm efficacy n=121, 94.5%). The practical assessment of the accuracy of the segmentation of arterial cross-sections (both the lumen and atherosclerotic plaques), considered the comparison of automatic and manual results. Manual results were obtained on the basis of determining points from peripheral cross-sections, which were automatically connected into one continuous contour using combined functions. These areas were considered as reference for assessing the accuracy of automatic methods. The obtained results confirmed the high efficiency of automatic methods: the mean absolute error was 1.5%, and standard deviation – 2%.

When analysing the obtained numerical results it was noted that the measure reducing the surface of the vascular lumen, based on the cross-section, is more restrictive in case of ellipse presence. Mean values were as follows: 8.6% in case of the common iliac artery, and 18.2% in case of the external iliac and common femoral arteries. We observed much higher measurement values of local tortuosity of the atherosclerotic arteries (0.3-1 radians), as compared to their anatomical course in a healthy subject (0-0.2 radians). Figure 3 presented the exemplary distribution of measure changes considering the entire artery.

**DISCUSSION**

Atherosclerosis is a common disease and its symptoms intensify with age. Such patients are additionally burdened with atherosclerotic organ complications leading to the compromise of the populations’ health condition. The above-mentioned include myocardial infarction, cerebral stroke, aortic aneurysms, and obliterative atheromatosis, including lower limb necrosis determined by vascular impatency, due to atherosclerotic lesions. Using the opportunities offered by the latest CTs, non-invasive diagnostics in the field of interest is possible. The study was devoted to the iliac and femoral segments performing segmentation and qualitative evaluation of atherosclerotic lesions. The femoral artery allows universal access to most endovascular procedures. Not all endovascular procedures may be performed by means of an alternative access. Thus, the condition of the femoral and iliac vessels often determines the possibility of surgical intervention. The arteries are evaluated on the basis of the following: actual diameter of blood flow, presence of atherosclerotic lesions, location of atheromatous plaques, arterial patency, arterial spatial system, depending on arterial tortuosity and presence of angular flexion. The presented tools were developed for the detection and assessment of atherosclerotic lesions creating new opportunities for surgeons planning management strategies (13, 14). These methods are based on statistical operations and mathematical morphology enabling vascular segmentation and quantitative evaluation of the number of atherosclerotic lesions, considering iliac and femoral arteries.

Manual inspection methods of the arteries are well known, including the evaluation of their topography and wall morphology, and atherosclerotic plaques presence. Most investigations concern carotid artery ultrasonography (15, 16). However, these are examinations performed by a physician subject to a certain degree of subjectivity, thus, incomparable. The above-mentioned examination enables to determine the anatomy of the arteries, their di-

**Fig. 3. Value of the angular vessel flexion in the iliac-femoral segment in a healthy person (red color) and that with atherosclerotic lesions (blue color)**
ameter, location of bifurcations, anatomical variations, as well as view possible loops and angular flexions (17). One may also detect and evaluate coexisting pathological lesions, such as aneurysms, dissection, and arteriovenous fistula development (18, 19). CT arteriography allows to visualize the arteries and their spatial reconstruction on the basis of blood flow, which together with the contrast fills the vessels (20). Thus, we can determine the anatomy, course, and atherosclerotic stenosis of the vessels. The above-mentioned information is supplemented by the possibility of three-dimensional reconstruction of blood flow (lumenography). Lumenography shows calcified atheromatous plaques, although ulceration analysis is more difficult. Hence, this last feature is best analysed on the basis of results obtained by means of Doppler ultrasonography or MR arteriography. Particularly accurate images are obtained by means of the latest generation magnetic resonances (3 Tesla) (15). On the basis of the above-mentioned, one can differentiate homogeneous from non-homogeneous plaques, and determine eventual cracks and possible internal bleeding. The evaluation of the arteries under investigation is minimally dependent on the experience of the physician performing the examination (18).

The Calcium Score is an example of the quantitative measurement of the degree of atherosclerosis (21). However, the results of the above-mentioned are only intended to be used as a prognostic factor, describing the quantitative amount of calcium carbonate inside the vascular wall. Thus, the received information enables to determine a certain fact, and connect it with the coexistence of concomitant diseases, or may be a prognostic factor of the occurrence of cardiovascular events (22, 23). In addition, thus obtained data allow the possible prediction or connection of the degree of atherosclerotic lesions in vascular areas, other than directly subjected to analysis (24).

The practical use of the study creates new possibilities for research into the assessment of changes, which occur in the vascular wall after stent and stent-graft implantation, as well as intraoperative risk. Further investigations might include the use of the methodology for the analysis of vascular images obtained by means of MRI. In the later stage there is the possibility to include the mathematical model for the analysis of the distribution of forces and interactions between the stent or stent-graft and vascular wall. Most likely, it will also be possible to determine the prognosis and risk, considering the functioning of endovascular equipment, long before treatment.

Thus far, an automatic system detecting atherosclerotic lesions and the course of the vessel has not been presented. Most investigations concerned the coronary and carotid arteries. The proposed system for the first time applies its methodology to the arteries. The practical use of its results might significantly facilitate the work of specialists performing endovascular procedures. An important advantage of the proposed quantitative analysis of atherosclerotic lesions is its possible use in the determination of the progression/regression of these lesions. Such data would not only be of great prognostic value, but also an indicator for pharmacological treatment. It is worth noting that the developed algorithm might in the future enable to evaluate other arteries, such as the aorta, arteries branching of the aortic arch, as well as visceral and lower extremity arteries.

REFERENCES


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