Application of deep learning techniques for segmentation of atherosclerotic carotid arteries by using ultrasound images

Branko Arsic[1,2], Smiljana Djorovic[2,3], Milos Anic[2,3], Igor Saveljic[2,4], Igor Koncar[5] and Nenad Filipovic[2,3]
[1]Faculty of Science, University of Kragujevac, Serbia
[2]Bioengineering Research and Development Center (BioIRC), Kragujevac, Serbia;
[3]Faculty of Engineering, University of Kragujevac, Serbia
[4]Institute of Information Technologies, Kragujevac, Serbia
[5]Faculty of Medicine, University of Belgrade, Serbia
e-mails: brankoarsic@kg.ac.rs; smiljana@kg.ac.rs; anicmilos95@gmail.com; isaveljic@kg.ac.rs; dr.koncar@gmail.com; fica@kg.ac.rs

Abstract— **In the era of personalized medicine and improved prediction power, the cardiovascular diseases such as carotid atherosclerosis have to be analyzed by using advanced machine learning techniques in order to better estimate the patient's condition and decrease the risk from severe catastrophic events over time, such as stroke and Transitional Ischemic Attack (TIA). Among various diagnostic imaging techniques, the US images were used in this study for the detection of segments of the carotid artery as this technique is low-cost and widespread in examination of carotid atherosclerosis. The clinical US images were analyzed by using deep learning techniques. The automatic segmentation of carotid artery's lumen has been done by using the U-Net based deep convolutional networks. The US images of carotid arteries underwent the preprocessing, such as resizing and classification of US images, as well as the annotation of lumen area. The whole dataset was randomly divided into, training, validation and testing sub-sets, while the model robustness was tested on unseen images (test dataset). The obtained results show high accuracy in region detection and segmentation (Precision - 0.90, Recall - 0.92, Dice coefficient (F1-score) - 0.91). The automatic extraction of US features such as carotid lumen gives the specific segmentation of individual patient-specific anatomy and can be used for further analysis of the patient, as well as for building up the patient-specific models for computational CFD simulations.**

I. INTRODUCTION

Carotid arteries are major blood vessels on the right and left side of the human neck which start from Common Carotid Artery (CCA) and branch into Internal Carotid Artery (ICA - supplies oxygenated blood to the brain) and External Carotid Artery (ECA - supplies oxygenated blood to the face and neck). Their role in the cerebrovascular system is of vital importance and therefore the malfunctions and diseases of carotid arteries have been considered and examined by experts such as medical scientists, biochemists and bioengineers.

One of the diseases in human cardiovascular system is carotid artery stenosis (CAS) which is caused by the atherosclerotic plaque deposition. Early detection of this disease is very important because if it is not adequately treated, it may potentially have deteriorating consequences, such as stroke and Transitional Ischemic Attack (TIA). Approximately 10% of ischemic strokes in the world is caused by carotid atherosclerosis [1].

Among the various diagnostic techniques, such as ultrasound (US), computed tomography angiography (CTA) and magnetic resonance angiography (MRA), the US is usually initially recommended CAS diagnostic examination. After obtaining the images using some of the above-mentioned techniques, additional analysis can be performed [2, 3]. The US images have been used in this study as this diagnostic procedure is low-cost and present at the first level of clinical care, while its improvement in view of image processing and extracted features can be beneficial for more detailed and faster analysis of patients. The automatic extraction of US features such as carotid lumen gives the specific segmentation of individual patient-specific anatomy and can be used for further analysis of the patient [4, 5], as well as for building up the patient-specific models for computational CFD simulations [6].

In the processing of medical imaging data, deep learning is a fast-developing technique with promising results in automatic classification and segmentation of medical images. Beside various applications in different medical fields using US medical images as input (e.g. lung, brain, breast, and liver imaging), in the domain of carotid arteries deep learning has been applied for the analysis of carotid US images that requires segmentation of the vessel wall, lumen, and carotid plaque composites. Convolutional neural networks (CNNs) are used for evaluation of the Intima-Media Thickness (IMT) of the CCA [7], lumen segmentation [8], as well as characterization of carotid plaque types [9]. The segmentation of complete carotid artery including carotid bifurcation is a challenging task due to typically lower quality of US images [10].

The approach presented in this paper provides automatic segmentation of carotid lumen based on CNNs that is suitable background for further creation of 3D patient-specific models and analysis of atherosclerotic patients, as well as for the examination of additional parameters that cannot be directly measured with the US technique. Such analysis can be obtained using CFD or computational atherosclerosis progression where patient-specific models based on automatic segmentation of carotid lumen can be used.

The paper is organized as follows: The applied deep learning methods and the used US imaging data are discussed in Section II. The results of the training of the U-Net based neural networks are presented in Section III, while Section IV discusses relevant work and concludes the paper.

II. MATERIALS AND METHODS

A. *Dataset of US images*

The dataset used for automatic segmentation of carotid artery consisted of the clinical US images as an input, obtained in the clinical study of the TAXINOMISIS project. In order to train and validate the applied deep learning methodology, the US dataset contained the original and annotated US images. The US images annotated by clinical experts are used for training, while the original images, as the ground truth are used for the validation. The dataset consisted of 108 patients who underwent the US examination (baseline time point), where each patient had captured carotid artery segments and carotid bifurcation in transversal and longitudinal projections. The US dataset included incorporation of US images using two procedures: traditional B-mode (gray-scale) US and Color-Doppler US, where both of these procedures produce two-dimensional (2D) cross-sectional images. The US images used in this study were anonymized according the data protection and safety regulations.

B. *Image Preprocessing*

Taking into consideration the proposed methodology and the low quality of the US images, image preprocessing is an important pre-step for many deep learning algorithms related to the image and instance segmentation, as well as objects detection tasks. In this case, the first step of the preprocessing is the automated isolation of the image region which contains the arterial tree under reconstruction. This is performed by selecting a static 512x512 pixels window for both arterial models, left and right. Special attention is paid to the window coordinates in order to the whole arterial tree is visible in the region. After this step, all images are labeled thus creating dataset with labeled regions for the lumen. In Figure 1, the first column consists of the examples of the original images, while the second column presents labeled images for the lumen. The additional steps included classification of longitudinal and transversal US images, as well as classification of B-mode and Color-Doppler US images.

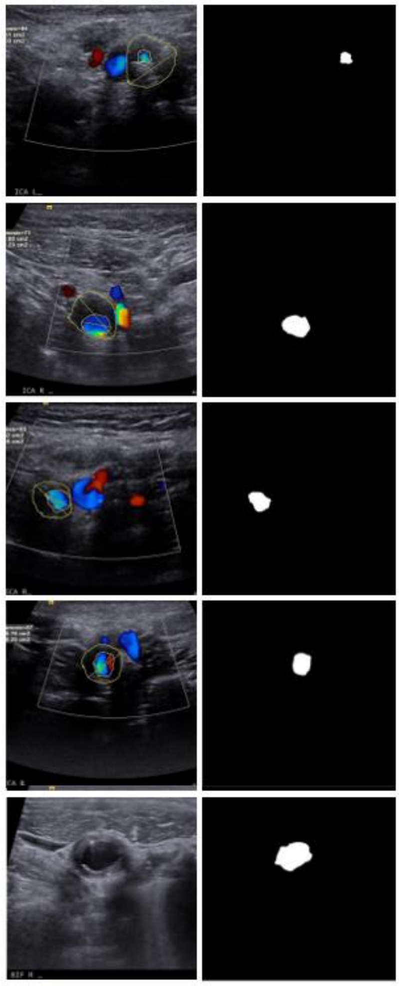

Figure 1. The carotid US images. The first column represents the original images and the second column represents the lumen masks.

C. *Image Segmentation*

The automatic segmentation of carotid artery lumen has been done using FCN-8s [11], [12], SegNet [13], and U-Net [14] - based deep convolutional networks. Beside the original versions of these architectures, we modified the U-Net and SegNet networks from the aspect of depth in order to test their capabilities to recognize the regions of interest. U-Net is a convolutional neural network for image segmentation with the most important application being in segmentation of medical images, based on encoder-decoder model. Our variant of U-Net is slightly modified from the original - it has two additional blocks in both encoder and decoder and uses batch normalization after each convolutional layer which proves to work a lot better on our data than the original U-Net model [15]. The model is trained with a combination of binary cross-entropy and soft dice coefficient as a loss function.

The US dataset explained in Section II A, was randomly divided into, training, validation and testing sub-sets by a ratio of 8:1:1 at the carotid artery level (either for the left or for the right arterial model). The total of 700 images have been taken out for training purposes and the remaining is used for validation and testing.

III. RESULTS

In order to present the results of the CNN training, binary classification task for image segmentation was considered. Four common classification metrics are considered for quantitative evaluation, including accuracy (ACC), precision (P), recall (R), and Dice coefficient. The results for the test dataset for lumen are shown in Table 1. The applied method is compared with thresholding technique and FCN-8s model with VGG16 as a backbone classifier [11]. Similar to U-Net, FCN model proved to work better with batch normalization. However, FCN-8s has almost twice as many trainable parameters than U-Net network, so the U-Net can be trained faster and it is more memory efficient. Similarly, U-Net architecture has almost twice as many trainable parameters than SegNet network. In Figure 2, the second column shows the examples of the predicted images for a lumen region.

TABLE I.
U-NET RESULTS ON TEST DATASET FOR LUMEN

Precision	Recall	Dice coefficient (F1-score)
0.90	0.92	0.91

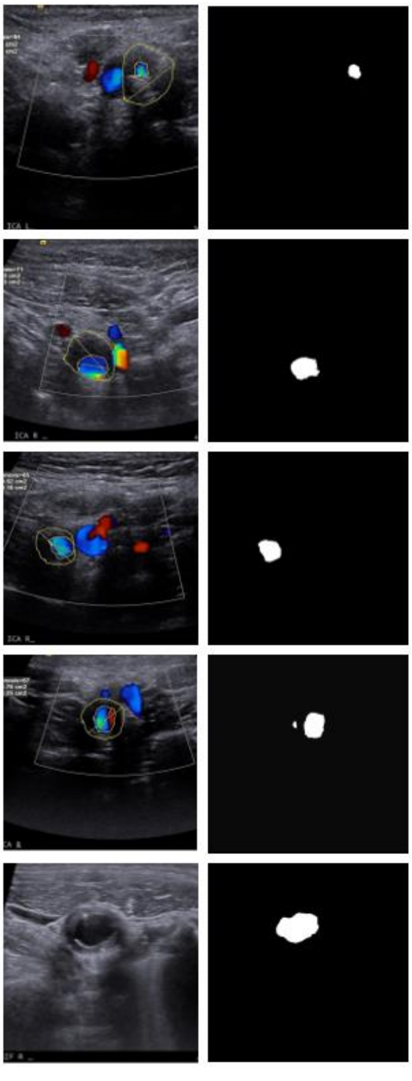

Figure 2. The carotid US images. The first column represents the original images, and the second column shows the predicted lumen regions.

IV. DISCUSSION AND CONCLUSION

In order to achieve more personalized medical treatments, better estimate the patient’s condition, decrease the risk from severe catastrophic events over time, and improve the risk stratification of patients with cardiovascular diseases such as carotid atherosclerosis, the application of advanced computational methods based on machine learning techniques is promising, showing significant results. Although the presented task is challenging due to significant noise, artifacts, shadowing, and reverberation in the US images which lead to their lower quality, this study provides the excellent results in automatic segmentation of carotid artery lumen using the US clinical images. The applied methodology relies on advanced deep learning techniques. All the tests were performed on GIGABYTE NVIDIA GeForce GTX 1080 Ti 11GB, GDDR5X, 352bit. Moreover, beside presented CNNs, there are many modifications of CNNs used to segment medical US images [16, 17].

The presented methodology enables efficient segmentation and extraction of the morphological parameters that can be also used for creation of 3D meshed volume models and computational simulations. Further application of CNNs can be extended to the carotid wall segmentation as well as characterization of different atherosclerotic plaque types (fibrous, lipid and calcified). This approach can contribute to faster examination of patients in clinical practice and better risk stratification of patients with atherosclerosis. Also, it directly contributes to computer-based modelling in improved building up the patient-specific 3D models for computational simulations.

ACKNOWLEDGMENT

This work is supported by the European Union’s Horizon 2020 research and innovation programme under grant agreements No 755320 – TAXINOMISIS. This article reflects only the author's view. The Commission is not responsible for any use that may be made of the information it contains. The paper is also funded by Serbian Ministry of Education, Science, and Technological Development [451-03-9/2021-14/200107 (Faculty of Engineering, University of Kragujevac)].

REFERENCES

[1] Chaturvedi, S., Sacco, R.: How recent data have impacted the treatment of internal carotid artery stenosis. J Am Coll Cardiol, 65(11), 134–43 (2015).

[2] Landry, A., Ainsworth, C., Blake, C. et al: Manual planimetric measurement of carotid plaque volume using three-dimensional ultrasound imaging. Med. Phys. (2007). Doi: 10.1118/1.2715487

[3] Chiu, B., Beletsky, V., Spence, J. D., et al: Analysis of carotid lumen surface morphology using three-dimensional ultrasound imaging. Phys. Med. Biol. (2009). Doi: 10.1088/0031-9155/54/5/004

[4] Madani, A., Beletsky, V., Tamayo, A., Munoz, C., Spence J. D.: High-risk asymptomatic carotid stenosis Ulceration on 3D ultrasound vs TCD microemboli, Neurology, (2011). Doi: 10.1212/WNL.0b013e31822b0090.

[5] Hashimoto, H., Tagaya, M., Niki, H., Etani, H.: Computer-assisted analysis of heterogeneity on B-mode imaging predicts instability

of asymptomatic carotid plaque, Cerebrovasc. Dis., (2009). Doi: 10.1159/000229554.

[6] Djorovic, S., Saveljic, I., Filipovic, N.: Computational Simulation of Carotid Artery: From Patient-Specific Images to Finite Element Analysis. J Serb Soc Comp Mech, 13: 120–129, (2019). Doi: 10.24874/jsscm.2019.13.01.08

[7] Menchón-Lara, R. M., Sancho-Gómez, J. L.: Fully automatic segmentation of ultrasound common carotid artery images based on machine learning, Neurocomputing, (2015). Doi: 10.1016/j.neucom.2014.09.066.

[8] Xie, M., Li, Y., Xue, Y. et al: Vessel lumen segmentation in internal carotid artery ultra-sounds with deep convolutional neural networks. IEEE International Conference on Bioin-formatics and Biomedicine (BIBM), San Diego, CA, USA, 2019, pp. 2393-2398, doi: 10.1109/BIBM47256.2019.8982980

[9] Lekadir, K., Galimzianova, A., Betriu, À., et al: A Convolutional Neural Network for Au-tomatic Characterization of Plaque Composition in Carotid Ultrasound. IEEE J. Biomed. Heal. Informatics, (2017). Doi: 10.1109/JBHI.2016.2631401

[10] Hashimoto, B. E.: Pitfalls in carotid ultrasound diagnosis, Ultrasound Clinics. (2011). Doi: 10.1016/j.cult.2011.08.006.

[11] Long, J., Shelhamer, E., and Darrell, T.: Fully convolutional networks for semantic segmentation, in Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition (2015). Doi: 10.1109/CVPR.2015.7298965.

[12] Simonyan, K., and Zisserman, A.: Very deep convolutional networks for large-scale image recognition, in 3rd International Conference on Learning Representations, ICLR 2015 - Conference Track Proceedings, 2015.

[13] Badrinarayanan, V., Kendall, A., Cipolla, R.: SegNet: A Deep Convolutional Encoder-Decoder Architecture for Image Segmentation, IEEE Trans. Pattern Anal. Mach. Intell., (2017). Doi: 10.1109/TPAMI.2016.2644615.

[14] Ronneberger, O., Fischer, P., Brox, T.: U-net: Convolutional networks for biomedical image segmentation, in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2015. Doi: 10.1007/978-3-319-24574-4_28.

[15] Zhou, X. Y., Yang, G. Z.: Normalization in training U-Net for 2-D biomedical semantic segmentation. IEEE Robot. Autom. Lett. (2019). Doi: 10.1109/LRA.2019.2896518

[16] Li, Y.: Segmentation of Medical Ultrasound Images Using Convolutional Neural Networks with Noisy Activating Functions, Stanford Edu, (2016).

[17] Smistad, E., and Løvstakken, L.: Vessel detection in ultrasound images using deep convolutional neural networks, in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), (2016). Doi: 10.1007/978-3-319-46976-8_4.