70TH ESCVS CONGRESS
& 7TH IMAD MEETING

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MODELING OF CARDOTID BIFURCATION AND PLAQUE BASED ON ULTRASOUND IMAGES

Nenad Filipovic[a,b], Andjela Blagojevic[a,b], Smiljana Tomasevic[a,b], Branko Arsic[b], Tijana Djukic[b]

[a]Faculty of Engineering University of Kragujevac, Kragujevac, Serbia, fica@kg.ac.rs

[b]BioIRC Bioengineering Research and Development center, Kragujevac, Serbia, smiljana@kg.ac.rs

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Risk stratification model

Computational model of plaque progression

Objectives

- Refinement of the existing multilevel computational model of plaque progression

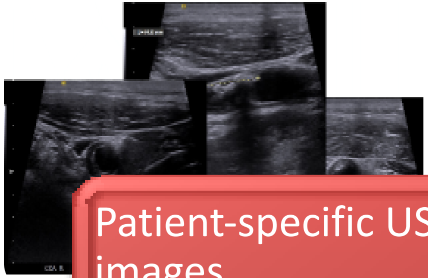
First level approach

1. Extension of 3D carotid artery reconstruction methods using the US images
2. Extension of 3D plaque characterization methods for more accurate plaque type identification in the US images

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 755320.

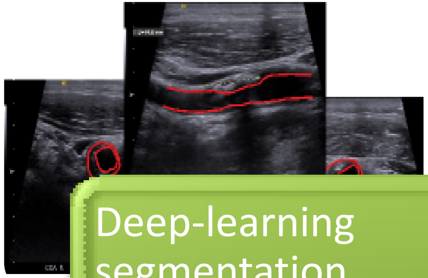
Risk stratification model

Methodology in 3D carotid artery reconstruction



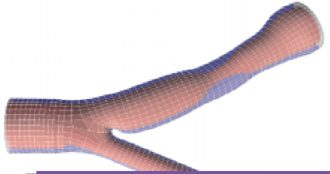
Patient-specific US images

- Longitudinal image
- Transversal images



Deep-learning segmentation

- Extract lumen segments
- Extract wall segments



3D reconstruction

- Adapt generic geometry to patient-specific data
- Generate 3D finite element mesh

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Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

US Dataset creation

- Dataset of original and annotated US images has been collected.
- The annotated images were used for development of US processing module, while the original images, as the ground truth were used for the validation.
- Imaging data from UBEO partner have been processed, as UBEO's dataset was the largest, having the high-quality images comparing to other clinical centers. Afterwards, the US dataset included data from NKUA.
- Each patient had captured the CCA, ICA and carotid bifurcation in transversal projections. CCA and ICA mainly had longitudinal projections. Initially, ECA was excluded from the US examination at the baseline time point. NKUA dataset contained patients with captured ECA, which enabled creation of more detailed models.
- The suitable images from data processing, 3D reconstruction and plaque characterization were stored in the training and test dataset.
- The US examination was performed in B mode and Color doppler mode.

The preprocessing of US dataset

- Annotation of carotid lumen and wall area
- Resizing/Cropping of US images to 512x512 pixels
- Classification of longitudinal and transversal US images
- Classification of B mode and Color doppler mode images

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Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

Methodology

i) Deep learning techniques for segment recognition

- Image preprocessing
- Experimental setup
- Image segmentation methodology

ii) 3D reconstruction of the carotid artery

- The adaptation of the generalized geometry to the specific patient, by using the detected segments (shapes) of the arterial wall (deep learning)
- Creation of FE model

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Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

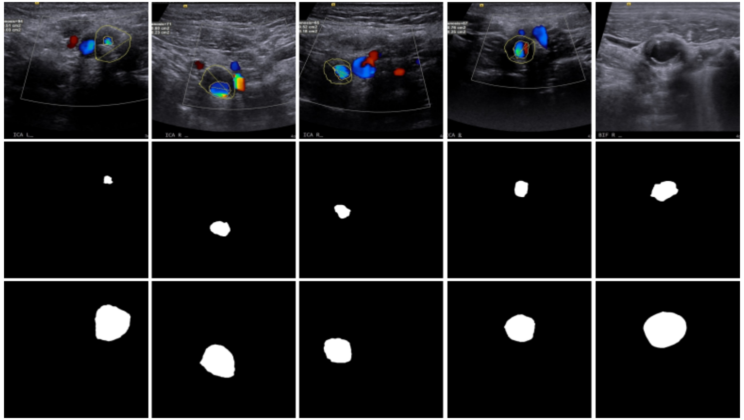
Methodology *i) Deep learning techniques for segment recognition*

Image preprocessing

- Automated isolation of the image region which contains the arterial tree under reconstruction (both left and right carotid models).
- Two datasets with labeled regions, one for the lumen and the second one for the wall.

Experimental setup

- Subfolders corresponding to the patients are randomly divided into training, validation and testing sets.
- Convergence of loss function and Dice coefficient values over training and validation data are performed for the lumen and wall segmentation tasks.



Carotid ultrasound images. The first row represents the original images, the second row represents the lumen masks, and the third row represents the wall masks.

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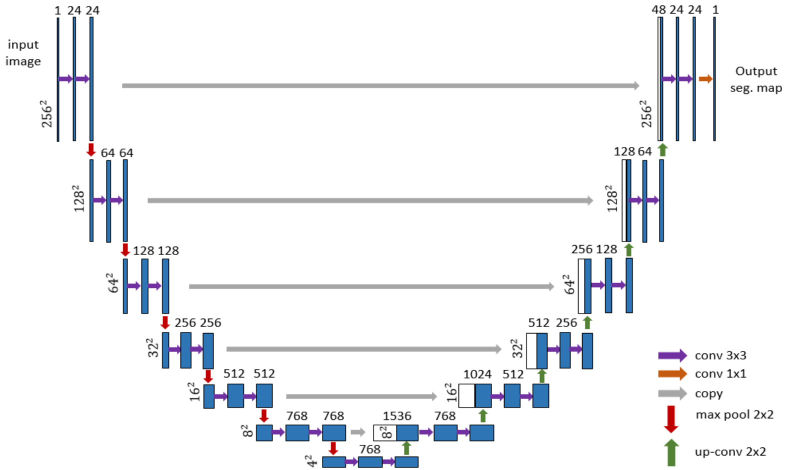
Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

Methodology *i) Deep learning techniques for segment recognition*

Image segmentation methodology

- The automatic carotid artery (lumen and wall) segmentation has been done using SegNet and U-Net based deep convolutional networks.
- Beside the original versions of these architectures, the U-Net and SegNet networks were modified from the aspect of depth in order to test their capabilities to recognize the regions of interest.



U-Net architecture. Blue boxes represent the feature maps, white boxes are the feature maps copied from the encoder and concatenated with the decoder feature maps. Spatial resolution is shown on the left side of feature maps, and the number of channels is written on top of boxes.

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Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

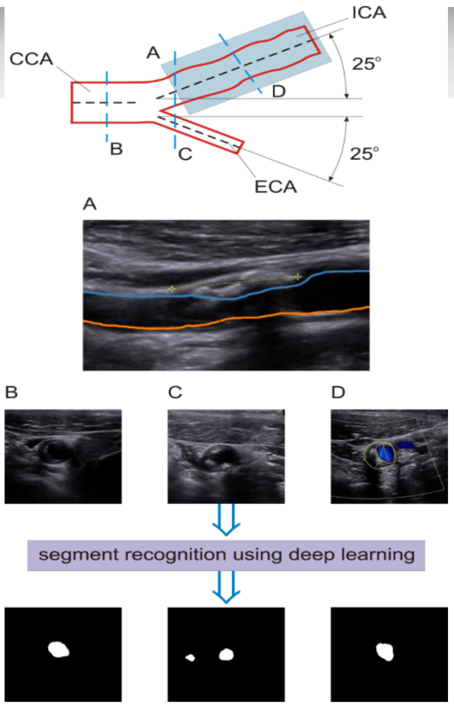
Methodology *ii) 3D reconstruction of the carotid artery*

3D reconstruction methodology

- One of the main problems with the patient dataset is the limited number of available 2D transversal cuts.
- In order to overcome the problem with the missing cuts, the generalized model was used as the basis. This basis is then adapted to the specific patient, by including the available data in the geometry.
- The US transversal cuts are used to detect the shapes of the arterial wall using the deep learning approach. The detected segments are then used to define the particular cross-sections.

Two approaches in computer-based 3D reconstruction of carotid wall

- The generalized model by fitting the shape of the segmented lumen (deep learning)
- The adaptation of the generalized geometry to the specific patient, by using the detected segments (shapes) of the arterial wall (deep learning)



The adaptation of the generalized model of the carotid artery using US images obtained for a specific patient.

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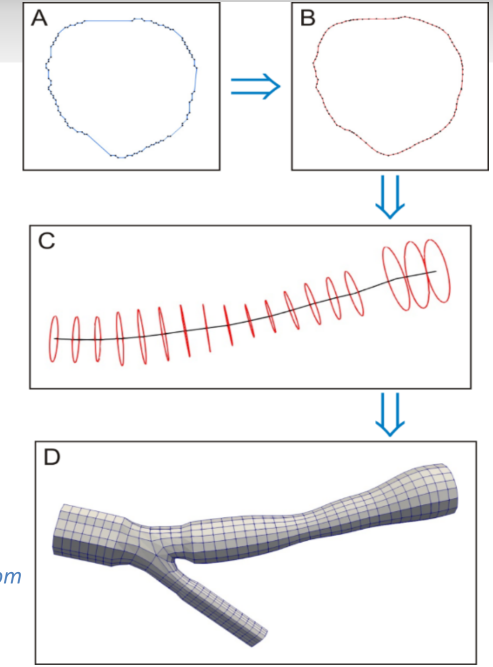
Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

Methodology *ii) 3D reconstruction of the carotid artery*

3D reconstruction methodology

- The 3D reconstruction process is performed using the structured meshing and algorithms[4].
- The vessel segment (A) is extracted from US image. The smoothing of the obtained curves is performed (B), by converting them to nonuniform B-spline curves. The cross-sections along the centerline are defined (C) and finally, the 3D FE mesh is generated (D).



*The process of 3D reconstruction; **A** – segment extracted from US image; **B** – nonuniform B-spline; **C** – parameterized centerline with cross-sections; **D** – 3D FE mesh.*

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[4] *A. M. Vukicevic, S. Çimen, N. Jagic, G. Jovicic, A. F. Frangi, and N. Filipovic, "Three-dimensional reconstruction and NURBS-based structured meshing of coronary arteries from the conventional X-ray angiography projection images," Sci. Rep., 2018, doi: 10.1038/s41598-018-19440-9.*

Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

Results & Validation

i) Image segmentation results for the lumen and wall

ii) 3D reconstruction of the carotid artery

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Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

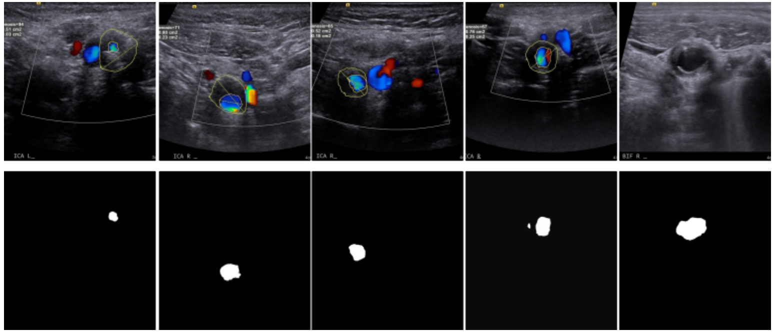
Results & Validation *i) Image segmentation results for the lumen and wall*

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

*U-Net results on test dataset for **lumen**.*

MODEL	Precision	Recall	Dice coefficient (F1-score)
WALL grayscale	0.9636	0.9634	0.9634
WALL colored	0.9874	0.987	0.9872

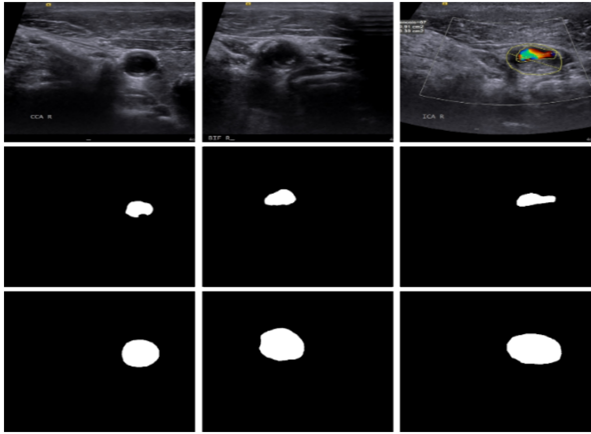
*U-Net results on validation dataset for carotid artery **wall**.*



*Carotid ultrasound images. The first row represents the original images, and the second row shows the predicted **lumen** regions.*

Model	Dice coefficient (F1-score)
WALL grayscale	0.92
WALL colored	0.94

*SegNet results on validation dataset for carotid artery **wall**.*



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All the tests are performed on GIGABYTE NVIDIA GeForce GTX 1080 Ti 11GB, GDDR5X, 352bit

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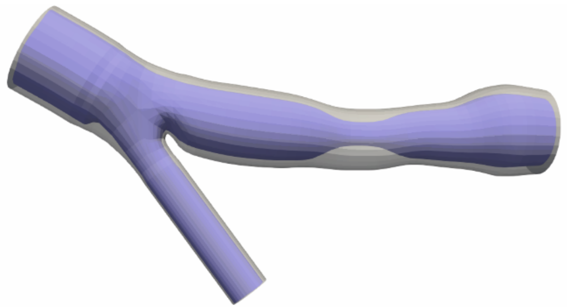
Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

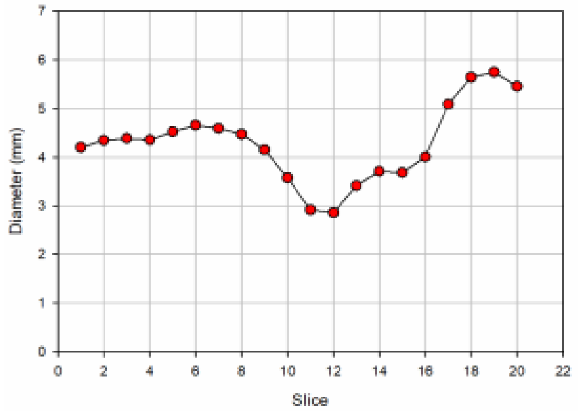
Results & Validation *ii) 3D reconstruction of the carotid artery*

Considered parameters: Plaque length and the percentage of stenosis

- In order to calculate the values of these quantities for the reconstructed models, the diameters of the reconstructed ICA branches were extracted on overall 20 cross-sections along the length of this branch.



*Patient **#049R** - Generated mesh with arterial wall.*



*Patient **#049R** - Measured diameters of the reconstructed ICA branch.*

The generalized model by fitting the shape of the segmented lumen (deep learning)

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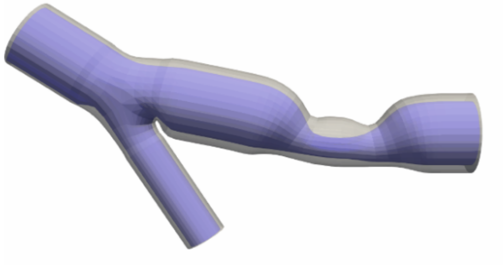
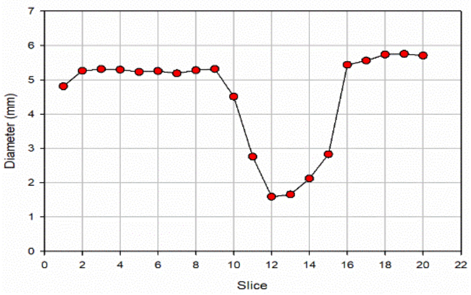
Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

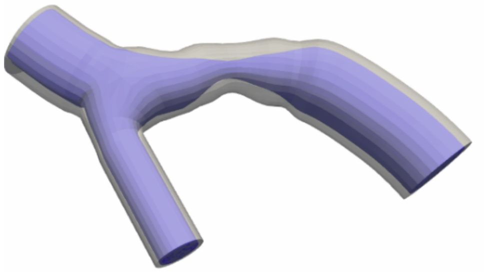
Results & Validation *ii) 3D reconstruction of the carotid artery*



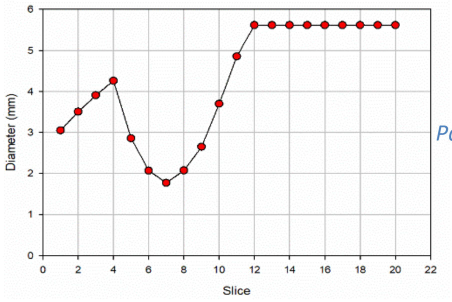
*Patient **#101R** - Generated mesh with arterial wall.*



*Patient **#101R** - Measured diameters of the reconstructed ICA branch.*



*Patient **#101L** - Generated mesh with arterial wall.*



*Patient **#101L** - Measured diameters of the reconstructed ICA branch .*

The generalized model by fitting the shape of the segmented lumen (deep learning)

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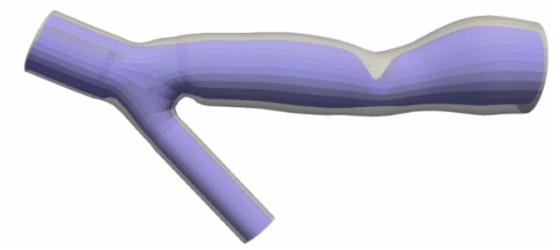
TAXINOMISIS

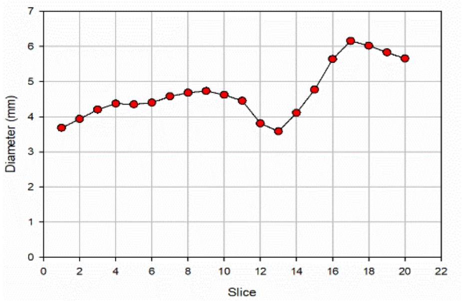
Risk stratification model

Extension of 3D carotid artery reconstruction methods using the US images

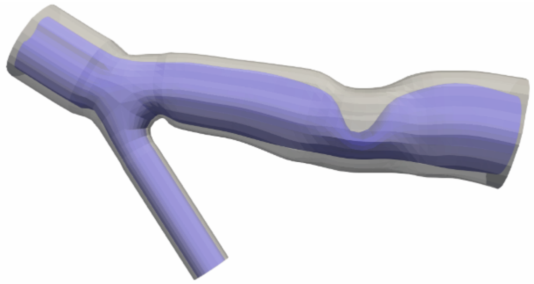
Results & Validation *ii) 3D reconstruction of the carotid artery*



Patient #082R - Generated mesh with arterial wall.



Patient #082R - Measured diameters of the reconstructed ICA branch.



Patient #082R - Generated mesh with arterial wall.

The generalized model by fitting the shape of the segmented lumen (deep learning)

The adaptation of the generalized geometry to the specific patient, by using the detected segments (shapes) of the arterial wall from transversal cuts (deep learning)

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TAXINOMISIS

Risk stratification model

Extension of 3D plaque characterization methods for more accurate plaque type identification in the US images

Dataset creation for plaque characterization

As extension of the created dataset for the 3D carotid reconstruction, the dataset for 3D plaque characterization includes the following:

- Overlapping the previously detected and segmented carotid lumen and wall area in transversal cross-sections and extraction of plaque area,
- Annotation and creation of three different masks corresponding to plaque components (fibrous, lipid, calcified), and creation of one mask for background color.

a) b) c)

Original data provided by clinical partners (a), extracted “ring” (b), annotated plaque (c).

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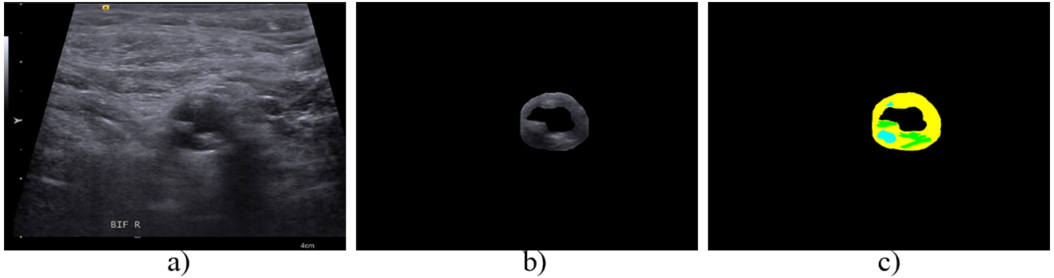
Risk stratification model

Extension of 3D plaque characterization methods for more accurate plaque type identification in the US images

Methodology *i) Deep learning techniques for segment recognition*

For multiclass image segmentation task three architectures were tested: Unet, SegNet and PSPNet (Pyramid Scene Parsing Network). For trained and tested models image input size was 512x512 pixels. Pixel map for the models was defined as follows:

- Background (0) is annotated with black color,
- Fibrous plaque (1) is annotated with yellow color,
- Lipid plaque (2) is annotated with blue color,
- Calcified plaque (3) is annotated with green color.



Original data provided by clinical partners (a), extracted "ring" (b), annotated plaque (c).

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Risk stratification model

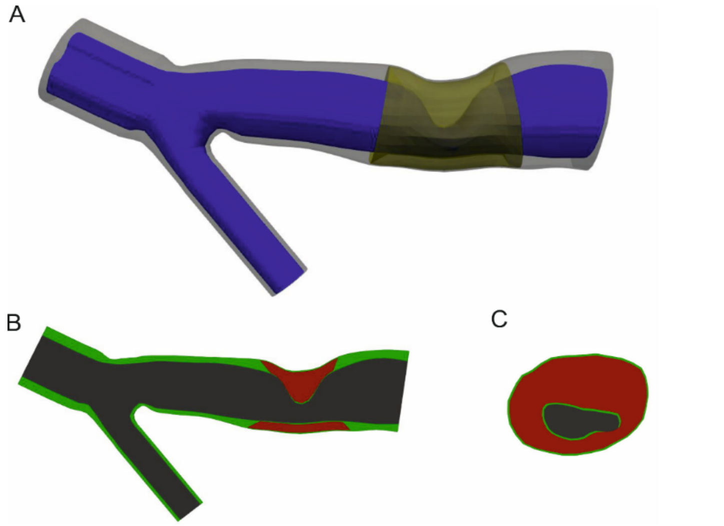
Extension of 3D plaque characterization methods for more accurate plaque type identification in the US images

Methodology *ii) 3D reconstruction of the carotid plaque*

Improved 3D reconstruction software which includes separation of plaque from the arterial wall and reconstruction of three plaque types, according to the data obtained from components segmentation using CNNs.

Plaque separation from the arterial wall was ensured in the reconstruction software in two steps:

1. The plaque was computationally located along the longitudinal direction of the ICA,
2. A layer of elements representing the plaque was extracted from the previously created finite element (FE) mesh of the ICA wall in radial direction.



The reconstructed model with separated plaque (A) with illustrated cross-sections in longitudinal (B) and radial (C) direction.

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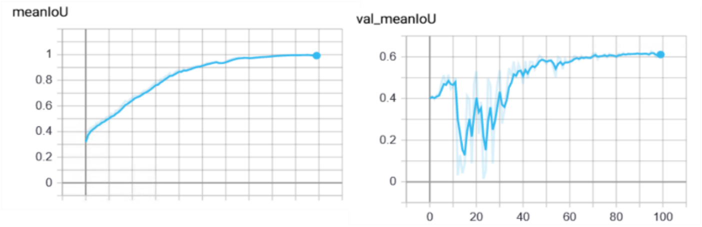
Risk stratification model

Extension of 3D plaque characterization methods for more accurate plaque type identification in the US images

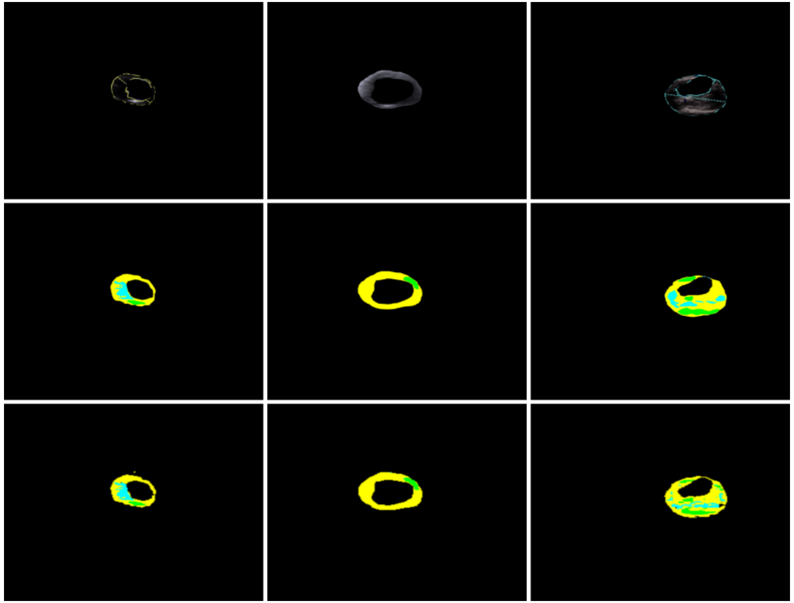
Results *i) Image segmentation results for the carotid plaque*

	TEST (Entire test set)
mean IoU	0.606
class-wise IoU	[0.998, 0.743, 0.220, 0.465]

U-Net results for the atherosclerotic plaque components segmentation. U-Net outperformed the SegNet and PSPNet .



Unet. MeanIoU values over train and validation datasets.



Atherosclerotic plaque zone. The first row represents the original images, the second row manually labeled images, and the third row represents multi-class prediction results.

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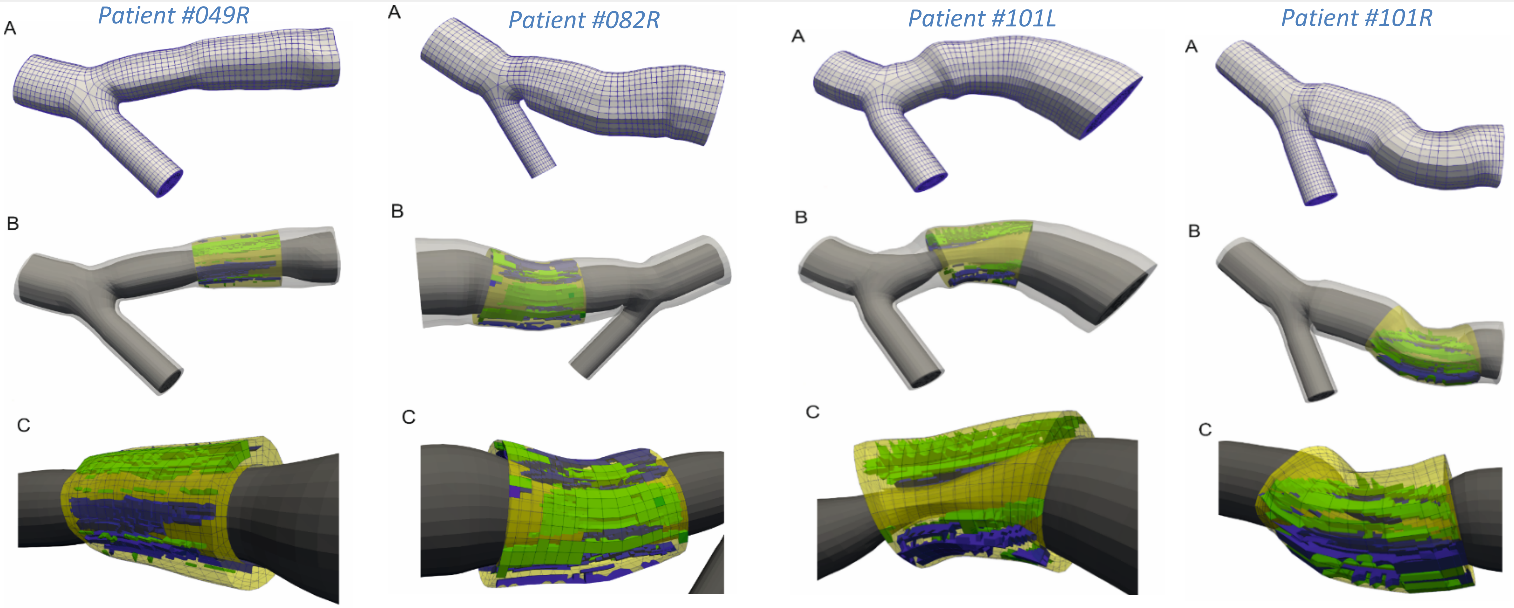
TAXINOMISIS

Risk stratification model

Extension of 3D plaque characterization methods for more accurate plaque type identification in the US images

Results *ii) 3D reconstruction of the carotid plaque*

The generated 3D FE mesh



A – Full model

B - Transparent model with colored plaque components

C – Augmented part with the FE elements defined as plaque

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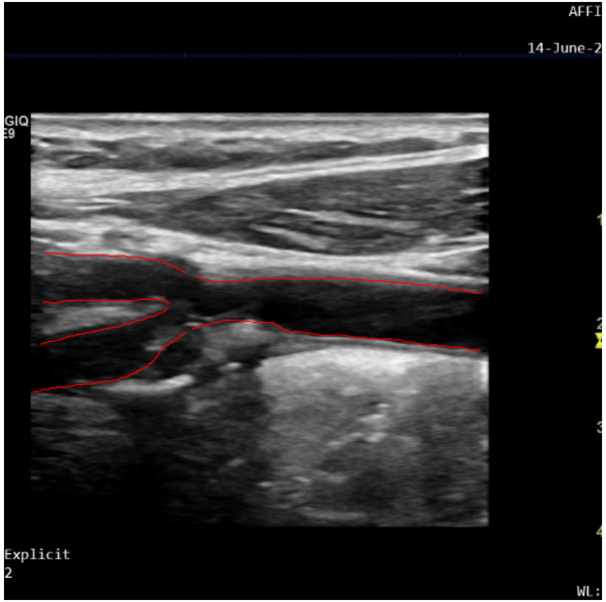
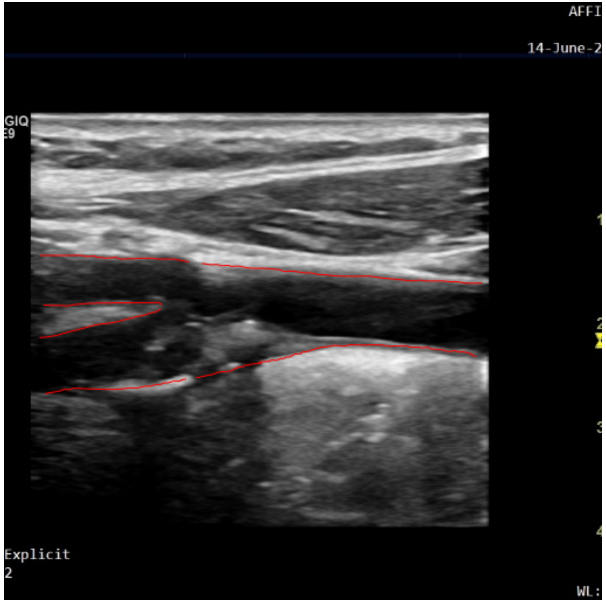
Risk stratification model

3D US model towards comparison of US and MRI

- **NKUA patient #20**
  - Bifurcation





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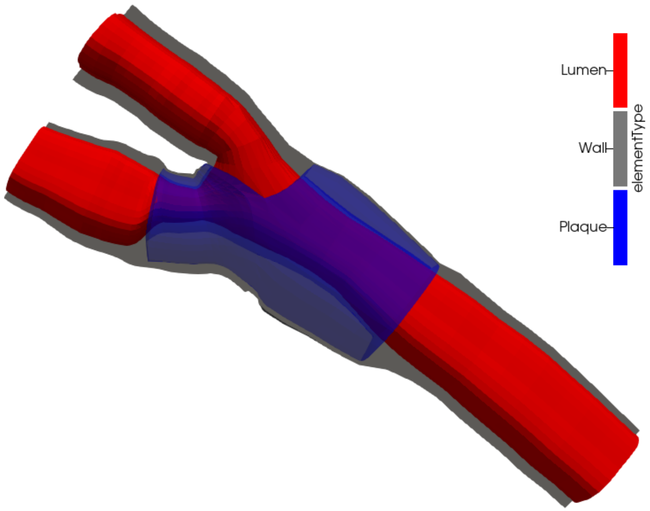
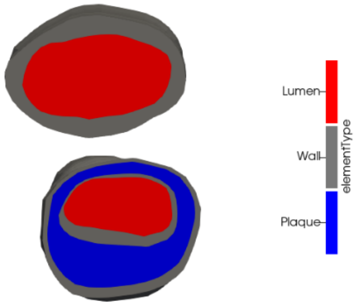
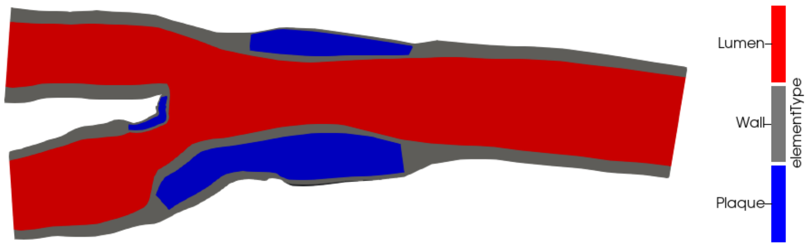
Risk stratification model

3D US model towards comparison of US and MRI



- NKUA patient #20





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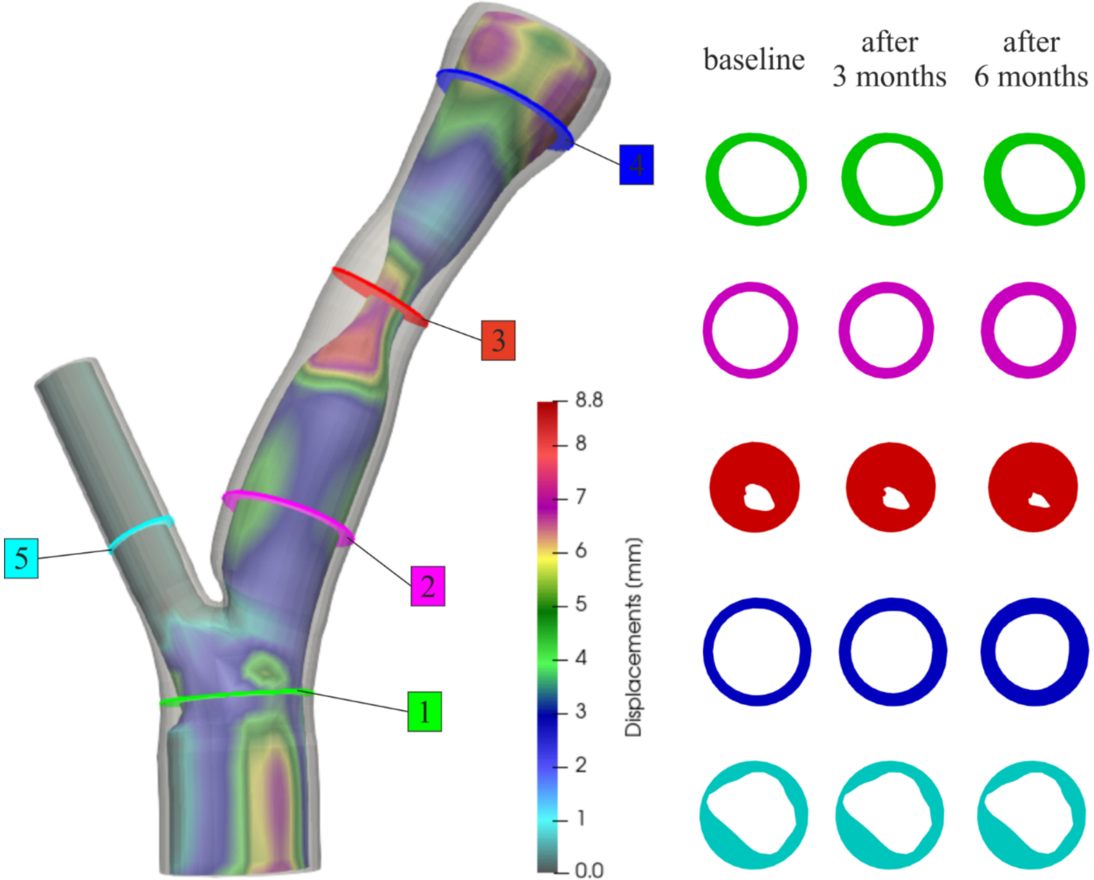
Example for carotid artery plaque progression



Risk stratification model

Conclusions

The proposed methodology contributes to the state-of-the-art by:

1. Training and deploying a deep learning model (U-net) for the image segmentation phase, related to the carotid lumen and wall segmentation, as well as characterization of three different plaque types (lipid, fibrous and calcified);
2. Computer-based automated 3D reconstruction method that is capable of generating a semi-generic geometrical model of the carotid artery, containing plaque types, that is adapted to the specific patient.

There are no many approaches that use presented or a similar technique to automatically reconstruct the carotid artery and plaque components after their segmentation based on CNN and using US as input.

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Risk stratification model

Conclusions

Future work

The development of *US processing module* is a continuous process which will be proceeded in future period through:

- Comparison of US and MRI models
- Enlarging the US dataset
- Further validation of models
- Increasing the plausibility of models

Risks

- Quality of US data
- Following of US protocol (covering CCA, ICA, ECA)
- Difficulties in annotation of plaque types
- Usability of each examined patient
- Difficulties of computational performances on different US datasets (from clinical centers)
- Lack of completed patient-specific features in 3D reconstruction and characterization due to low US images quality / insufficient cross sections

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Thank you

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