Computer Methods and Programs in Biomedicine 158 (2018) 71–91

Contents lists available at ScienceDirect

Computer Methods and Programs in Biomedicine

journal homepage: www.elsevier.com/locate/cmpb

Blood vessel segmentation algorithms — Review of methods, datasets and evaluation metrics

Sara Moccia[a,b], Elena De Momi[a], Sara El Hadji[a,*], Leonardo S. Mattos[b]

[a] Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milan, Italy
[b] Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genoa, Italy

ARTICLE INFO

Article history:
Received 3 November 2017
Revised 23 December 2017
Accepted 2 February 2018

Keywords:
Blood vessels
Medical imaging
Review
Segmentation

ABSTRACT

Background: Blood vessel segmentation is a topic of high interest in medical image analysis since the analysis of vessels is crucial for diagnosis, treatment planning and execution, and evaluation of clinical outcomes in different fields, including laryngology, neurosurgery and ophthalmology. Automatic or semi-automatic vessel segmentation can support clinicians in performing these tasks. Different medical imaging techniques are currently used in clinical practice and an appropriate choice of the segmentation algorithm is mandatory to deal with the adopted imaging technique characteristics (e.g. resolution, noise and vessel contrast).
Objective: This paper aims at reviewing the most recent and innovative blood vessel segmentation algorithms. Among the algorithms and approaches considered, we deeply investigated the most novel blood vessel segmentation including machine learning, deformable model, and tracking-based approaches.
Methods: This paper analyzes more than 100 articles focused on blood vessel segmentation methods. For each analyzed approach, summary tables are presented reporting imaging technique used, anatomical region and performance measures employed. Benefits and disadvantages of each method are highlighted.
Discussion: Despite the constant progress and efforts addressed in the field, several issues still need to be overcome. A relevant limitation consists in the segmentation of pathological vessels. Unfortunately, not consistent research effort has been addressed to this issue yet. Research is needed since some of the main assumptions made for healthy vessels (such as linearity and circular cross-section) do not hold in pathological tissues, which on the other hand require new vessel model formulations. Moreover, image intensity drops, noise and low contrast still represent an important obstacle for the achievement of a high-quality enhancement. This is particularly true for optical imaging, where the image quality is usually lower in terms of noise and contrast with respect to magnetic resonance and computer tomography angiography.
Conclusion: No single segmentation approach is suitable for all the different anatomical region or imaging modalities, thus the primary goal of this review was to provide an up to date source of information about the state of the art of the vessel segmentation algorithms so that the most suitable methods can be chosen according to the specific task.

1. Introduction

Blood vessel analysis plays a fundamental role in different clinical fields, such as laryngology, oncology [1], ophthalmology [2], and neurosurgery [3–6], both for diagnosis, treatment planning and execution, and for treatment outcome evaluation and follow up.

The importance of vessel analysis is supported by the constant introduction in clinical practice of new medical technologies aimed at enhancing the visualization of vessels, as endoscopy in Narrow Band Imaging (NBI) [7] and cone beam Computed Tomography (CT) 3D Digital Subtraction Angiography (DSA) [8]. At the same time, standard techniques, such as Magnetic Resonance Angiography (MRA) and Computed Tomography Angiography (CTA), are constantly improved to enhance vascular tree visualization [9–11].

Manual segmentation of blood vessels is an expensive procedure in terms of time and lacking intra- and inter-operator repeatability and reproducibility. On the other hand, semi-automatic or automatic vessel segmentation methods require at least one expert clinician to segment or to evaluate the segmentation results obtained. In addition, support for the development and evalua-

* Corresponding author.
E-mail addresses: sara.moccia@polimi.it, sara.moccia@iit.it (S. Moccia), sara.elhadji@polimi.it (S. El Hadji).

https://doi.org/10.1016/j.cmpb.2018.02.001

Nomenclature

2D	Bidimensional
3D	Tridimensional
3DRA	Tridimensional Rotation Angiography
Acc	Accuracy
AUROC	Area Under the Receiver Operating Characteristic Curve
AUPRC	Area Under the Precision–Recall Curve
CNN	Convolutional Neural Network
CRF	Conditional Random Field
CT	Computed Tomography
CTA	Computed Tomography Angiography
DSA	Digital Subtraction Angiography
DSC	Dice Similarity Coefficient
EM	Expectation-Maximization
FCCRF	Fully Connected Markov Random Field
FMM	Fast Marching Method
FN	False Negative
FP	False Positive
FPrate	False Positive rate
FCN	Fully Convolutional Networks
GF	Gabor Filter
GPU	Graphic Processor Unit
GS	Gold Standard
GVF	Gradient Vector Flow
H	Hessian matrix
HD	Hausdorff distance
IR	Infrared
κ	Cohen's κ coefficient
LNND	Lattice Neural Network with Dendritic
LS	Level Set
MCC	Matthews Correlation Coefficient
M	Metric tensor for minimum cost path
MCP	Minimum Cost Path
MF	Matched Filter
MHTT	Multiple Hypothesis Template Tracking
MIP	Maximum Intensity Projection
MRA	Magnetic Resonance Angiography
MRF	Markov Random Field
MRI	Magnetic Resonance Imaging
NBI	Narrow Band Imaging
NPV	Negative Predictive Value
OCT	Optical Coherence Tomography
OF	Overlap until first error
OOF	Optimal Oriented Flux
OT	Overlap with the clinically relevant part of the vessel
OV	Overlap
PBT	Probabilistic Boosting Tree
PF	Particle Filtering
PPV	Positive Predictive Value
PSO	Particle Swarm Optimization
RACAL	RAdius-based Clustering ALgorithm
RANSAC	RANdom SAmple Consensus
RF	Random Forest
ROC	Receiver Operating Characteristic
Se	Sensitivity
Sp	Specificity
STAPLE	Simultaneous Truth And Performance Level Estimation
SVM	Support Vector Machine
TN	True Negative
TP	True Positive
US	Ultrasound

tion of such algorithms is still poor as publicly available image datasets with associated Gold Standard (GS) segmentation are currently limited to specific anatomical regions, such as retina [12]. However, automatic or semi-automatic blood vessel segmentation could assist clinicians and, therefore, are topics of great interest in medical research, as demonstrated by the high amount of papers annually published in this field. Indeed, an extensive literature already exists on vessel segmentation and in the past years different reviews on vessel segmentation algorithms have been published, such as [12–19]. However, due to the strong development in the field, updated reviews are required to analyze and summarize the actual state of the art.

This review aims at analyzing a wide spectrum of the most recent and innovative vessel segmentation techniques found in the literature, reporting on state of the art approaches based on machine learning (Section 5), deformable model (Section 6) and tracking methods (Section 7). Moreover, it reports on the most commonly adopted metrics for the evaluation of segmentation results (Section 3) and identifies the available testing datasets (Section 4).

The goal of this review is to provide comprehensive information for the understanding of existing vessel segmentation algorithms by summarizing their advantages and limitations. Each segmentation approach is first analyzed in the general context of image segmentation and then in the specific context of vessel segmentation. For each segmentation category, papers are discussed, illustrating their benefits and potential disadvantages. In addition, summary tables reporting performance measures are presented for each category. The paper concludes with a discussion on future directions and open issues in the field of vessel segmentation.

A summary of the papers analyzed in this review considering year of publication, anatomical region and imaging technique is reported in Table 1. In addition, Fig. 1 highlights the categories of vessel segmentation algorithms analyzed in the following sections of this paper.

2. Algorithm workflow

As shown in Fig. 1, in vessel segmentation algorithms the input image first undergoes a pre-processing step, which typically concerns noise suppression, data normalization, contrast enhancement and conversion of color image to grayscale image. Since different imaging modalities produce images characterized by different resolution, noise and contrast, different pre-processing techniques have to be employed. An exhaustive review on pre-processing algorithms is presented in [122].

The core of the vessel segmentation workflow concerns the segmentation process, which can be classified in four different categories:

- Vessel enhancement
- Machine learning
- Deformable models
- Tracking

Through vessel enhancement approaches, the quality of vessel perception is improved, e.g. by increasing the vessel contrast with respect to background and other non-informative structures. A strong and established literature on vessel enhancement approaches already exists. Examples include matched filtering [123], vesselness-based approaches [124], Wavelet [67] and diffusion filtering [125]. Due to the extensive literature on the enhancement methods and the wideness of this subject, in this review we will not deal with it. A complete review on the topic can be found e.g. in [12].

The vessel enhancement can be followed by a thresholding step to directly obtain the vessel binary mask. Nonetheless, modern methods employ the enhanced vasculature as a preliminary