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Standard and fenestrated endograft sizing in EVAR planning: Description and validation of a semi-automated 3D software

Iván Macía[a,f,g,*], Mariano de Blas[c,f], Jon Haitz Legarreta[a,f], Luis Kabongo[a,f], Óscar Hernández[b], José María Egaña[d,f], José Ignacio Emparanza[e,f], Ainhoa García-Familiar[d], Manuel Graña[g]

[a] Vicomtech-IK4 Foundation, Donostia/San Sebastián, Spain[1]
[b] eMedica S.L., Zamudio, Spain
[c] Department of Radiology, Donostia University Hospital, Donostia/San Sebastián, Spain
[d] Department of Vascular Surgery, Donostia University Hospital, Donostia/San Sebastián, Spain
[e] Department of Clinical Epidemiology, Donostia University Hospital, Donostia/San Sebastián, Spain
[f] Biodonostia Health Research Institute, Donostia/San Sebastián, Spain
[g] Computational Intelligence Group, Computer Engineering Faculty, University of the Basque Country, Donostia/San Sebastián, Spain

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ABSTRACT

An abdominal aortic aneurysm (AAA) is a pathological dilation of the abdominal aorta that may lead to a rupture with fatal consequences. Endovascular aneurysm repair (EVAR) is a minimally invasive surgical procedure consisting of the deployment and fixation of a stent–graft that isolates the damaged vessel wall from blood circulation. The technique requires adequate endovascular device sizing, which may be performed by vascular analysis and quantification on Computerized Tomography Angiography (CTA) scans. This paper presents a novel 3D CTA image-based software for AAA inspection and EVAR sizing, *eVida Vascular*, which allows fast and accurate 3D endograft sizing for standard and fenestrated endografts. We provide a description of the system and its innovations, including the underlying vascular image analysis and visualization technology, functional modules and user interaction. Furthermore, an experimental validation of the tool is described, assessing the degree of agreement with a commercial, clinically validated software, when comparing measurements obtained for standard endograft sizing in a group of 14 patients.

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1. Introduction

An abdominal aortic aneurysm (AAA) is a pathological condition consisting of an abnormal dilation of the abdominal aorta, exceeding more than 50% its normal diameter [8]. Aneurysms tend to grow, and eventually may rupture, with a high mortality rate. Elective surgery is usually performed when the diameter exceeds 5.5 cm [16]. The traditional surgical approach based on an open repair, has been steadily substituted by the endovascular aneurysm repair (EVAR), a minimally invasive technique involving the deployment and fixation of a stent graft that excludes the damaged wall from circulation.

EVAR requires pre-procedural planning consisting of image-based patient anatomy assessment for endograft selection and sizing. Relevant measurements are obtained from high resolution Computerized Tomography Angiography (CTA) scans of the

* Corresponding author at: Vicomtech-IK4 Foundation, Donostia/San Sebastián, Spain. Tel.: +34 943309230; fax: +34 943309393.
E-mail address: imacia@vicomtech.org (I. Macía).
[1] URL: http://www.vicomtech.org (Vicomtech-IK4 Foundation)

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abdominal area, using specific vascular image analysis modules or applications [1,12]. Furthermore, it has been recently demonstrated [23] that developing 3D surgical planning technology may have an impact on the intervention outcome, due to a more accurate endograft sizing and intervention planning.

As surgical practice and device design evolve, more complicated cases are being treated endovascularly, requiring increasingly complex pre-surgical analysis, and custom stent–graft designs. In the case of AAAs, these sometimes require the provision of fenestrations (windows) for subsidiary arteries, specifically when the aneurysm extends proximally covering the infrarenal space, and preventing fixation. Due to the specificity and complexity of the analysis, innovative computational tools supporting the design of fenestrations and custom-made endografts are required. However, there is not enough clinical evidence on how these cases should be addressed [4,3,14]. Current commercial solutions for EVAR planning range from general workstations with advanced planar or curved reformattings around a centerline to specific tools for the aorta. The need to reduce costs has recently led to a strong competition to provide vascular surgeons with fast, robust, accurate and intuitive endograft sizing tools coping with all the raised issues. A few softwares have started to provide solutions for planning complex fenestrated endografts.

In this paper, we present a 3D EVAR endograft sizing tool, named *eVida Vascular*, first introduced in Ref. [19], which includes advanced visualization and analysis tools for managing standard as well as complex cases, including the provision of fenestrations (windows) in the endograft fabric, while providing a trade-off between automation, speed, robustness, usability, intuitiveness, and flexibility requirements. A novel semi-automatic and robust vascular analysis procedure was developed for this application, based on a prior single-click segmentation of the aortic tree, centerline extraction, including subsidiary arteries, and vessel graph analysis. The method is complemented with the ability to segment missing branches to deal with low contrast scans or severe artifacts. This vascular analysis provides the input for an intuitive visualization interface, combining 3D renderings of the aortic tree and centerlines, supporting 2D views, planar reformattings and visual cues in different synchronized layouts. It features three operation modes or workflows providing fast and accurate sizing of endografts with automatic length and diameter estimation, namely the standard AAA endograft sizing mode, the fenestrated endograft sizing mode, and a free interaction mode allowing further freedom to the surgeon in taking measurements along the aorta centerline and branches. The fenestrated module allows the interactive definition of fenestrations through symbolic stents and endograft, better representing the deployment situation in cases with large aortic neck curvatures. Such combination of features is not present in other softwares.

We provide a description of the *eVida Vascular* application, explaining the vascular image analysis and visualization, as well as the different modes of operation. In addition, we report a validation comparing results of *eVida Vascular* with those of a commercial radiology 3D workstation with an AAA sizing module, used routinely in our clinical setting, in order to establish the degree of agreement in diameter and length quantification between both tools.

The outline of the article is as follows. Section 2 presents some important background facts, including clinical facts about AAA and EVAR, image analysis technologies for EVAR planning, and existing commercial solutions. Section 3 describes a set of pre-requisites or requirements for the development of a 3D tool for endograft sizing. Section 4 describes the vascular image analysis technology developed for *eVida Vascular*. Section 5 details the functional modules and interface of *eVida Vascular*. Section 6 presents the experiments performed for validation and the results obtained. The advantages and performance of the tool are discussed in Section 7, and finally, Section 8 presents the conclusions and future work.

2. Background

2.1. Abdominal aortic aneurysm

Abdominal aortic aneurysms develop between the renal and iliac arteries; they are defined as an infrarenal aortic diameter of more than 30 mm [22]. AAAs are asymptomatic, and tend to grow slowly, with a rupture risk directly correlated with the diameter. AAAs exceeding a diameter of 5.5 cm should be referred to a vascular surgeon for treatment [16]. Mortality rate after rupture is between 65% and 85% [13,24], causing roughly about 15,000 deaths per year in the US [7] and 8,000 deaths per year in the UK [24].

Open surgical repair by anastomosis of a synthetic conduit has been performed since the 1950s without major changes in the technique. Endovascular aneurysm repair (EVAR) is nowadays the preferred surgical procedure to treat AAAs, involving the deployment and fixation of a stent–graft inside the aorta via catheterism, which excludes the aneurysm wall from blood circulation. For correctly excluded aneurysms, the pressure exerted on the aortic wall decreases, leading to an eventual reduction in size, and, thus, decreasing the rupture risk.

Advantages of EVAR over open surgical repair include: lower perioperative morbidity and mortality, specially reduced 30-day mortality rates, and shorter recovery times, because there is no need for laparotomy and aortic cross-clamp [21]. The major EVAR complications are endoleaks, which are defined as a persistent flow into the excluded aneurysm sac due to incorrect sealing, endograft defects or breakdown, or retrograde blood flow from collateral vessels [25]. Endoleaks may cause aneurysm growth, and associated rupture risk may lead to re-intervention. Thus, lifelong surveillance is required, usually performed with Computerized Tomography Angiography (CTA) scans, at least yearly.

Complex aortic aneurysms correspond to situations where either there is not enough infrarenal space for fixation of the endograft, the so-called “landing zone”, or the aneurysm extends upwards beyond the renal arteries (suprarenal and thoraco-abdominal aortic aneurysm). They require the provision of fenestrations in the endograft, the use of branched endografts, often custom-made, or the chimney technique [11], so that the blood is allowed to flow through the subsidiary arteries. In absence of published clinical trials, results are promising thanks to the rapid evolution of the technique [11].

2.2. EVAR planning

EVAR planning requires the quantification of diameters and lengths along the aorta and its subsidiary branches for endograft device sizing. A standard endograft is selected in the majority of cases from a set of off-the-shelf models in catalog. According to Ref. [12], aneurysm measurements are more accurate when performed using a 3D workstation, especially when tortuosity is larger. Furthermore, Kicska et al. state that an automated vessel analysis, in combination with vascular landmark identification, may significantly contribute in reducing the post-processing time.

These 3D measurements are usually based on a combination of a 3D view of the patient-specific anatomy of the aorta and supporting planar reformattings. which include basic orthogonal and oblique sections, Curved Planar Reformattings (CPRs) [10] depicting the whole lumen in a single plane, and sections along the vessel. CPRs are computed from the centerline or medial axis [2,18] of the aorta and its main branches. The challenge during centerline calculation is to obtain a regularized medial curve whose normal sections

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