Medical Engineering & Physics 36 (2014) 822–830

Contents lists available at ScienceDirect

Medical Engineering & Physics

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

Hemodynamics in the cephalic arch of a brachiocephalic fistula

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ARTICLE INFO

Article history:
Received 15 August 2013
Received in revised form 22 January 2014
Accepted 8 March 2014

MSC:
76Z05
92C10
92C35

Keywords:
Brachiocephalic
Fistula
Cephalic arch
Intimal hyperplasia
Stenosis

ABSTRACT

The care and outcome of patients with end stage renal disease (ESRD) on chronic hemodialysis is directly dependent on their hemodialysis access. A brachiocephalic fistula (BCF) is commonly placed in the elderly and in patients with a failed lower-arm, or radiocephalic, fistula. However, there are numerous complications such that the BCF has an average patency of only 3.6 years. A leading cause of BCF dysfunction and failure is stenosis in the arch of the cephalic vein near its junction with the axillary vein, which is called cephalic arch stenosis (CAS). Using a combined clinical and computational investigation, we seek to improve our understanding of the cause of CAS, and to develop a means of predicting CAS risk in patients with a planned BCF access. This paper details the methodology used to determine the hemodynamic consequences of the post-fistula environment and illustrates detailed results for a representative sample of patient-specific anatomies, including a single, bifurcated, and trifurcated arch. It is found that the high flows present due to fistula creation lead to secondary flows in the arch owing to its curvature with corresponding low wall shear stresses. The abnormally low wall shear stress locations correlate with the development of stenosis in the singular case that is tracked in time for a period of one year.

1. Introduction

The outcome of patients with end stage renal disease (ESRD) undergoing hemodialysis depends on a functioning vascular access. Although a variety of techniques have been developed for providing hemodialysis access, there have been no major advances for the past three decades. This contributes to the fact that hemodialysis access dysfunction is one of the most important causes of mortality in the hemodialysis population. In addition, the expense of providing ESRD care in the US is a significant portion of the Medicare budget, totaling $32.9 billion in 2007, of which a significant portion is spent on placement and maintenance of vascular access [1]. Obstacles to long term fistula access include prevention and maintenance of venous stenosis. This investigation considers hemodynamic contributions to the primary mode of failure, cephalic arch stenosis (CAS), for dialysis patients with a brachiocephalic fistula (BCF).

1.1. Background

Native AVF have the lowest rate of complications and are recommended for vascular access [1–3]. The type of AVF with the best outcomes is the radiocephalic fistula (RCF); however, this access often fails to mature in elderly patients with underlying vascular disease, particularly in diabetics [4,5]. The second recommended access is the brachiocephalic fistula (BCF), which has a mean duration of function of only 3.6 years in contrast to RCF, which often exceed 5 years [5].

The BCF is a high-flow conduit for hemodialysis created by vascular surgeons in which the cephalic vein is joined to the brachial artery, typically in an end-to-side or side-to-side arrangement. The cephalic arch is the final bend in the cephalic vein prior to its junction with the axillary vein. The cephalic vein and arch geometry are illustrated in Fig. 1 as is the downstream connecting axillary vein. In this figure, d is the diameter, α is the cephalic arch angle, and R is its radius of curvature. The blood enters the cephalic arch from the right.

1.2. Postulated origins of cephalic arch stenosis

One of the leading hypotheses is that cephalic arch stenosis results from neointimal hyperplasia due to locally low shear

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http://dx.doi.org/10.1016/j.medengphy.2014.03.001
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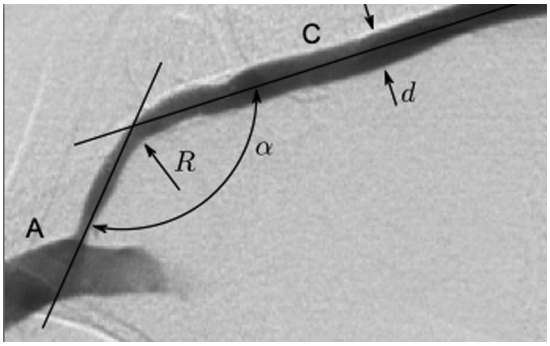

Fig. 1. Geometric parameters characterizing the cephalic arch (C is the cephalic vein; A is the axillary vein). Arch angle (α); Radius of curvature (R); Diameter of cephalic vein (d).

stresses on the vessel wall. Research suggests the possibility that hemodynamic forces, including wall shear stress, play a critical role in the regulation of vessel diameter. The diameter changes locally in order to maintain values of the shear stresses within an acceptable or target range. This mechanism is often referred to as *adaption* (see for example [6,7]). In the presence of low wall shear stresses, the intimal layer experiences growth due to the proliferation of smooth muscle cells from the media layer. Critical thresholds of wall shear stresses for veins are provided in Table 1. The wall shear stress values for a normal vein range from 0.076 to 0.76 Pa, [8]. It is noted, however, that the etiology of stenosis is primarily derived from arterial studies; therefore, it must be confirmed that the adaption process also applies to the venous system.

1.3. Clinical and computational studies

The leading cause of BCF failure is due to stenosis in the cephalic arch [11]. This is a recently recognized phenomenon and is often termed cephalic arch stenosis (CAS). Once CAS occurs, it leads to head and neck swelling, high venous pressures and resultant thrombosis with complex and difficult treatment options [8,12,13]. The arch is elastic, resistant to repeated angioplasty, and often requires stent placement resulting in further stenosis. Our experience at the University of Chicago shows that CAS is a common problem among dialysis patients with BCF. A retrospective review of 97 patients with BCF over a five year period shows that CAS occurred in 77% of the subjects, with the median time to development being 779 days (CI 666–892) [12]. Miller et al. [14] find that fistula flow reduction via banding of the juxta-anastomotic segment may reduce the incidence of intimal hyperplasia induced CAS in patients with BCF access.

There are several computational studies specifically regarding the brachiocephalic fistula. He et al. develops a protocol based on contrast-free MRI and 3D CFD for assessment of hemodynamic parameters and geometry changes in a brachiocephalic fistula. Results are provided for a single patient-specific geometry He et al. [15]. The study finds non-physiologic, disturbed flow in the AVF and spiral flow in the vein. Temporally averaged wall shear stresses were found to decrease in the vessel over the time period from 4 to 7 months. Sigovan et al. [16] performs a study looking at the feasibility of using a noncontrast-enhanced MRI and CFD protocol to relate the hemodynamic changes to vascular remodeling over a three month time period in both brachiocephalic and brachiobasillic fistulae. In another study, Kharboutly et al. [17] investigated the relationship between fluid flow and vascular alterations in a brachiocephalic fistula. Flow recirculation and associated negative wall shear stresses outside the normal physiological range are observed on the venous outflow side. An alternative approach to 2D or 3D modeling is a 1D network model of the fistula and connecting vessels. This approach has been recently used on various fistula configurations including the brachiocephalic [18,19]. The following related studies are also noted. Several investigations consider the flow in the radiocephalic fistula, see for example, Sivanesan et al. [20]; Niemann et al. [21]; Carroll et al. [22]. In addition, there are numerous studies where the primary emphasis is on the local modeling of the anastomosis region without considering details of the outflow (cephalic) vein. See for example, McGah et al. [23] and references therein.

Table 1
Critical wall shear stress levels for normal veins [7–10].

Condition	Critical WSS levels (Pa)
Postulated intimal hyperplasia	<0.076
Vein (minimum)	0.076
Vein (maximum)	0.76
Endothelial denudation	>40

1.4. Objectives

The purpose of this research is to describe the methodology used to create patient-specific CFD models that are used to determine the hemodynamics within the cephalic vein and arch in patients with a BCF. The computational model can help elucidate the hemodynamic contributions to the etiology of cephalic arch stenosis in BCFs. More broadly, the present investigation provides a unique opportunity to investigate the influence of hemodynamics on neointimal hyperplasia and stenosis in veins (compared to arteries where a better understanding exists) under extreme hemodynamic conditions resulting from the post-fistula environment.

2. Clinical and computational methods

The clinical and computational methodology used in this study involving multiple disciplines is described. Whereas similar investigations have emphasized detailed modeling (3D) of a small number of patient-specific hemodynamic flows, the present investigation develops a combination of *in vivo* measurements and computational models having short turnaround times that can be utilized in a clinical setting. In particular, the CFD model will be combined with clinically available – and cost effective – imaging technology, such as two-dimensional venograms, to develop a realistic representation of the hemodynamics within patient-specific cephalic arch geometries. Note that the use of MRI is not possible with ESRD patients owing to the toxicity of the markers used [24]. There are non-contrast MRI techniques that could be used; however, most routine MRI studies lack the spatial resolution of venography and are quite lengthy by comparison to venography, which typically is performed in 5 minutes.

2.1. Clinical data and imaging

After the patient is enrolled, pre-operative venogram, Doppler velocity measurement of the cephalic arch, and whole blood viscosity (WBV) are obtained. This data is again obtained at three months and one year. The venogram is performed as follows with simultaneous blood flow measurements. The patient has their fistula punctured with a 21-gauge needle near the arterial anastomosis directed toward the stenosis (either venous or arterial). The needle is exchanged for a 5 French dilator, and a digital subtraction venogram encompassing the outflow from puncture site to the right heart is performed. Any stenosis is measured using electronic calipers and defined. Any significant hemodynamic stenosis, defined as greater than 50% narrowing of the expected luminal diameter (75% by area), is treated with balloon angioplasty