Investigation of hemodynamic effect of stent wires on renal arteries in patients with abdominal aortic aneurysms treated with suprarenal stent grafts

Abstract

Purpose: The purpose of the study was to investigate the hemodynamic effect of stent struts (wires) on renal arteries in patients with abdominal aortic aneurysms (AAA) treated with suprarenal stent grafts.

Materials and Methods: Two sample patients with AAA undergoing multislice CT angiography pre-and post-suprarenal fixation of stent grafts were selected for inclusion in the study. Eight juxtarenal models focusing on the renal arteries were generated from the multislice CT datasets. Four types of configurations of stent wires crossing the renal artery ostium, namely single wire centrally crossing, single wire peripherally crossing, V-shaped wire centrally crossing and multiple wires peripherally crossing were simulated in the segmented aorta models. The blood flow pattern, flow velocity, wall pressure and wall shear stress at the renal arteries pre-and post-stent grafting were analyzed and compared using a two-way fluid structure interaction analysis. The stent wire thickness was simulated with a diameter of 0.4 mm, 1.0 mm and 2.0 mm, and hemodynamic analysis was performed at different cardiac cycles.

Results: The interference of stent wires with renal blood flow was mainly determined by the thickness of stent wires, and the type of configuration of stent wires crossing the renal ostium. The flow velocity was reduced by 20-30% in most of the situations when the stent wire thickness increased to 1.0 mm and 2.0 mm. Of 4 types of configuration, the single wire crossing centrally resulted in the highest reduction of flow velocity, ranging from 21% to 28.9% among three different wire thicknesses. Wall shear stress was also dependent on the wire thickness, which decreased significantly when the wire thickness reached 1.0 and 2.0 mm.

Conclusion: Our preliminary study showed that the hemodynamic effect of suprarenal stent wires in patients with AAA treated with suprarenal stent grafts was determined by the thickness of suprarenal stent wires. Research findings in our study are useful for follow-up of patients treated with suprarenal stent grafts to ensure long-term safety of the suprarenal fixation.

Keywords: Abdominal aortic aneurysm, blood flow, flow velocity, suprarenal stent graft, simulation, renal ostium

Introduction

Endovascular repair of abdominal aortic aneurysm (AAA) has been reported to be an effective alternative to conventional open surgery since its introduction into the clinical practice more than a decade ago [1-3]. With experience gathered, it was found that 30-40% of patients were excluded from the traditional infrarenal fixation of stent grafts due to complicated infrarenal aneurysm necks, either because of short necks (less than 10 mm), severe angulation (more than 60 degrees) or poor quality (extensive calcification or presence of thrombus). Therefore, a modification of the aortic stent grafts, suprarenal fixation has been developed to accommodate these patients unsuitable for infrarenal stent grafting [4-6]. Suprarenal fixation of stent grafts involves placing an uncovered suprarenal component above the renal arteries with aim of acquiring proximal fixation without compromising the renal blood flow or renal function. Although short to mid-term results are satisfactory, long-term safety of the suprarenal fixation of stent grafts is yet to be determined [7, 8].

The concern of long-term outcomes of suprarenal fixation is manifested in two folds: first, the long-term safety of placing the suprarenal stents across the renal arteries is not known with regard to its effect on the renal arteries or renal function; second, the interference of suprarenal stent struts/wires with the renal artery ostium in terms of morphological changes in relation to the configuration/number of stent wires crossing the renal artery ostium is not fully understood. Our previous study has addressed the latter point showing that the renal artery ostium demonstrated morphological changes following suprarenal fixation [9], while the effect of stent wires on renal blood flow has not been systematically studied. Therefore, the purpose of this study was to perform a computer simulation based on patients' data and investigate whether there is any significant interference of suprarenal stent wires with subsequent renal blood flow, based on variable stent wire crossing and different wire thicknesses.

Materials and Methods

Patient data selection

2 sample patients with AAA undergoing suprarenal fixation of stent grafts were selected for inclusion in the study. The stent grafts used in our study were Zenith AAA endovascular stent graft with a suprarenal uncovered component of 2.5 cm placed above the renal artery for acquisition of proximal fixation. Pre-and post-stent grafting CT scans were performed with a multislice CT scanner 16x0.5 mm beam collimation (Toshiba Medical Imaging Systems, Kingsbury, UK), and scanning protocol was as follows: section thickness 1.0 mm, pitch 2.0, reconstruction interval of 1.0 mm and gantry rotation time was 0.5 second. Pre-and post-stent grafting multislice CT angiography scans were performed with an intravenous injection of 100 ml of non-ionic contrast media (Niopam 300, Bracco UK Ltd. High Wycombe) administered at a rate of 2 ml/second with a fixed scan delay of 30 seconds. The left and right renal artery ostia were measured 4.92 mm and 4.10 mm, 4.80 mm and 5.20 mm in diameter for patient 1 and 2, respectively. Table 1 lists measurements of the length of renal arteries, distance between the entry point (abdominal aorta) to the renal arteries in both pre-and post-stent grafting aorta models.

Configuration of stent wires crossing the renal artery ostium

Original DICOM data (digital imaging and communication in medicine) pre-and post-stent grafting were transferred to a workstation equipped with Analyze V 7.0 (AnalyzeDirect, Inc., Lexana, KS, USA) for generation of 3D reconstructed images.

Generation of intraluminal images of the stent wires in relation to the renal artery ostium was performed using a CT number thresholding technique, which was described before [10]. In these two cases, the suprarenal stent wires were found to cross the renal artery ostium in four different configurations, which were previously reported [10, 11], namely: single wire centrally crossing (patient 2), single wire peripherally crossing (patient 1), V-shaped wire centrally crossing (patient 2) and multiple wires peripherally crossing (patient 1). Figure 1 presents the diagrams of these four types of configurations.

Segmentation of CT volume data

Segmentation of CT volume data was performed with a semi-automatic segmentation technique involving CT number thresholding, region growing and objects creation and separation. For generation of 3D AAA model with inclusion of only main abdominal aorta and its branches, the lowest and highest CT thresholds were set at 200 HU and 400 HU (Hounsfield unit) respectively to remove all of the soft tissues, bone structures and stent wires while keeping the contrast-enhanced artery branches; for generation of 3D AAA model with inclusion of endovascular stent grafts, the lowest threshold was set at 500 HU to remove all of the soft tissues and contrast-enhanced vessels while only keeping the high-density stent wires. Figures 2 shows the 3D AAA models from the CT data of patient 1 pre-and post-suprarenal stent grafting.

Generation of aorta mesh models

After segmentation, 3D surface objects were created using the module of surface extractor which is available on the Analyze software package, and the 3D surface objects were saved in the STL (stereolithography)', a common format for computed-aided design and rapid prototyping. The 'STL' file was converted into the CAD (computer aided design) model files using the CATIA V5 R18 (Dassault Systèmes, Inc., Suresnes Cedex, France).

The aorta mesh model consists of 3 parts in each patient: part 1 refers to the blood flow model of pre- and post-stent grating, while part 2 indicates the artery wall model of pre- and post-stent grafting, and part 3 is the blood flow model of post stent grafting with placement of the simulated suprarenal stent wires.

For advanced mesh modelling, the blood flow model (part 1) was generated by hexahedral volume meshes using ANSYS ICEM CFD 11 (ANSYS, Inc., Canonsburg, PA, USA). The blood wall model (part 2) was generated by tetrahedral volume meshes using ANSYS Meshing 11 (ANSYS, Inc., Canonsburg, PA, USA). The blood flow model with insertion of the suprarenal stent graft (part 3) was generated by tetrahedral volume meshes using ANSYS ICEM CFD 11 (ANSYS, Inc., Canonsburg, PA, USA). The structure and fluid mesh models of patient 2 are shown in Figure 3. The maximum elements of the blood wall model and flow model were composed of 17,247 and 82,650 elements, respectively.

Simulation of suprarenal stent wires in relation to the renal artery ostium

Although the segmented AAA models were generated with CT number thresholding which focuses on the high-density stent wires, detailed configuration of suprarenal stent wires crossing the renal artery ostium could not be displayed in the final mesh models. In order to simulate the intraluminal configuration of stent wires crossing the renal artery ostium, we generated a few models with a simulated wire thickness of 0.4 mm, 1.0 mm and 2.0 mm, respectively. Figure 4 shows meshing models of the suprarenal stent struts.

The stent strut model was defined by tetrahedral volume mesh and mesh elements of stent strut model were between 9,790 and 23,471 elements.

The stent strut model reflects the realistic clinical situation after implantation of suprarenal stent grafts in patients with AAA. The actual wire thickness of the Zenith suprarenal stent component is 0.4 mm, so we chose the simulated wire thickness to be 0.4 mm in diameter. As there is a potential opportunity for blood materials to build up on the stent surface over a certain period of time leading to the thickening of stent wires, we also simulated the wire thickness to be 1.0 mm and 2.0 mm respectively in this study. Before simulating the stent struts crossing the renal ostium, the non-strut crossing models were first generated as a reference in each patient based on the post-stent grafting data.

In summary, there were 4 entire aorta models in total (both pre-and post-stent grafting) comprising the abdominal aorta, aortic aneurysm, renal arteries and common iliac arteries. In addition, another 8 juxtarenal models focusing only on the renal artery ostium were generated to study specifically the flow changes to the renal arteries (one pre-stenting model plus 3 models with different stent wire thicknesses in each patient). For the four different types of stent wire crossing, we just changed the position of stent wires in each model to produce different configuration of wire crossing. Therefore, altogether 12 models were tested in our study.

Computational two-way fluid solid dynamics

In order to ensure that our analysis reflects the realistic environment of human blood vessel, normal physiological hemodynamic conditions should be considered for the 3D numerical simulations. This allows studying the aneurysmal fluid mechanics by taking into account the instantaneous fluid forces acting on the wall and the effect of the wall motion on the fluid dynamic field. The fluid and materials properties for different entities were referenced from a previous study [12]. To simulate the realistic situation in patients with AAA treated with suprarenal stent grafts, the blood flow was started at the level of celiac axis, then inside the aortic aneurysm, and flow out to the renal arteries and common iliac arteries. The boundary conditions are time-dependent [13]. The velocity inlet (abdominal aorta at the level of celiac axis) boundary conditions are taken from the referenced value showing measurement of the aortic blood velocity (Figure 5A). A time-dependent pressure is also imposed at the outlets (Figure 5B).

The fluid (blood) is assumed to behave as a Newtonian fluid, as this was known for the larger vessels of the human body. The suprarenal stent within the blood is set as no-material property. The fluid density was set to 1060 kg/m^3 and a viscosity of 0.0027 Pa s, corresponding to the standard values cited in the literature [13]. The flow was assumed to be incompressible and laminar. Given these assumptions, the fluid dynamics of the system is fully governed by the Navier-Strokes equations, which are shown as following:

$$\text{Continuity}: \quad \nabla \cdot \vec{v} = 0 \qquad (1)$$

$$\text{Momentum}: \quad \rho \frac{\partial \vec{v}}{\partial t} + \rho \vec{v} \cdot \nabla \vec{v} = -\nabla p + \mu \nabla^2 \vec{v} + \mathrm{f} \qquad \text{in } {}^F\Omega(t) \qquad (2)$$

where $\vec{v}$ is the blood velocity vector, p is the blood pressure, ρ is the blood density, μ is the blood viscosity, f is the body force at time t acting on the fluid per unit mass, ∇ is the gradient operator, and ${}^F\Omega(t)$ is the fluid domain at time t.

The solid (blood wall) is assumed to be elastic material and isotropic. The wall is set at 1.0 mm thick in both pre- and post-stented AAA models. The solid density was set to 1120 kg/m^3, a Poisson ratio of 0.49, and a Young's modulus of 1.2 MPa, corresponding to the standard values cited in the literature [14]. From these assumptions, the structures dynamics of the system are fully governed by the equations showing below:

$$\text{Momentum}: \quad \rho a_i = \sigma_{ij,j} + \rho \mathrm{f}_i \qquad \text{in } {}^S\Omega(t) \qquad (3)$$

$$\text{Equilibrium condition}: \quad \sigma_{ij} n_i = t_i \qquad \text{on } {}^S\Gamma(t) \qquad (4)$$

$$\text{Constitutive}: \quad \sigma_{ij} = D_{ijkl}\varepsilon_{kl} \qquad \text{in } {}^S\Omega(t) \qquad (5)$$

where a_i is the acceleration of material point, σ_{ij} is the stress tensor, ρ is the solid density, f_i is the force per unit mass at time t, n_i is the outward pointing normal on the surface wall ${}^S\Gamma(t)$, t_i is the surface traction vector, D_{ijkl} is the Lagrangian elasticity tensor, ε_{kl} is the strain tensor, and ${}^S\Omega(t)$ is the structural domain at time t.

In order to validate our results, we performed the simulation using a two-way coupled fluid-structure interaction (FSI). The governing equation of the fluid domain was solved using the ANSYS CFX 11 (ANSYS, Inc., Canonsburg, PA, USA). The governing equation of the structural domain was solved using the ANSYS Simulation 11 (ANSYS, Inc., Canonsburg, PA, USA). The FSI application was run with ANSYS CFX 11 with transient simulation (time-dependent), and the coupling time step is set at 0.025 s, with a total duration of 0.9 s with 0.9 s indicating the late diastolic pulsatile waveform. We simulated a single cardiac cycle same as that *in vivo* condition which is divided into the systolic and diastolic phases. The systolic phase starts from 0 s to 0.6 s while the diastolic phase ranges from 0.6 s to 0.9 s. This was applied to achieve a fully developed flow at the side of the renal ostium, as is shown in Figure 6. The meshes are deformable during the CFD analysis.

Based on the referenced parameters, the two-way FSI analysis of the simulation was performed with the blood flow simulated at different cardiac cycles (systolic and diastolic phases) in the aortic aneurysm, renal arteries and common iliac arteries using the ANSYS Multiphysic (ANSYS, Inc., Canonsburg, PA, USA). Blood flow pattern, wall pressure, and wall shear stress at the level of renal arteries before and after stent-graft implantation were calculated and compared.

Results

Hemodynamic analysis was successfully performed in all of these aorta models, based on different cardiac cycles. The general flow patterns generated in the abdominal aorta models with placement of stent graft were in agreement with the literature [12-14]. As the study focuses on the effect of suprarenal stent struts on the renal arteries, we only presented the results related to the renal arteries in terms of flow velocity, flow pattern, wall pressure and wall shear stress.

Hemodynamic analysis-flow velocity at the renal arteries

Table 2 provides the calculated peak flow velocity to the renal arteries in these simulated models. The flow velocity was calculated at the distal outlets of each renal artery. The low velocity at the right renal artery in patient 2 is due to the relatively large diameter of the renal artery. Our results showed that the flow velocity to the renal artery was mainly determined by the thickness of stent wires and type of stent wires crossing in relation to the renal artery ostium. Flow velocity was slightly decreased by up to 5% with a wire thickness of 0.4 mm in all types of configuration except the type of singe wire centrally crossing. For the single wire crossing centrally, it was found that the flow velocity to the renal artery was decreased by 21.1-28.9%, independent of the thickness of stent wires, as is shown in table 2. When the stent wire thickness increased to 1.0 and 2.0 mm, flow velocity was decreased by more than 10% and as high as nearly 30% in most of the situations, indicating that the wire thickness is the determinant factor in the flow analysis.

Similarly, flow pattern changes to the renal artery in the presence of stent struts crossing were dependent on the wire thickness. The velocity vectors' effect with a stent wire thickness of 0.4 mm, 1.0 mm and 2.0 mm was shown in Figure 7 (B-D) when compared to the non-strut crossing (Fig 7A). As is shown in the images, the laminar flow pattern to the renal arteries observed in pre-stent grafting became turbulent in the presence of stent wire crossing, and this is especially obvious when a single wire crossed the renal ostium centrally (Fig 7 E, F).

Hemodynamic analysis-wall pressure at the renal arteries

The maxiaml wall pressure did not show significant changes after implantation of the suprarenal stent grafts, even if in the presence of stent struts crossing the renal artery ostia. The wall pressure was found to increase slightly at the proximal part of right renal artery after stent struts crossing when the wire thickness increased to 1.0 mm and 2.0 mm (Fig 8).

Hemodynamic analysis-wall shear stress at the renal arteries

The areas of high wall shear stress are different to the high pressure areas. The areas of high wall shear stress are mainly situated in regions of enhanced recirculation or vertices. In our study, these locations are on the inner side of the renal arteries, as shown in Fig 9A. After suprarenal stent graft implantation, there is a significant drop in maximum wall shear stress, and this is especially apparent when the wire thickness increased to 1.0

mm and 2.0mm, as is shown in Fig 9B-D, when compared to the wire thickness of 0.4 mm (Fig 9B).

Discussion

Our preliminary study provides insight into the treatment outcomes of suprarenal fixation of stent grafts, although it was only based on two sample patients. The importance of our findings is demonstrated in two unique aspects which are different from previous reports: first, the AAA models were generated from real patients' data, which reflects the actual clinical situation, thus we believe our results are valid and can be translated to clinical practice. Second, simulation of stent wires crossing the renal artery ostium was verified by previous experience, which demonstrates the type of stent wire configuration in relation to the renal artery ostium based on 3D intraluminal visualization. Moreover, various thicknesses of stent wire diameter were simulated in the aorta models to demonstrate the potential effect of suprarenal stents on renal blood flow. Therefore, our results could be used as guidance for patients' follow-up, especially from a long-term point of view.

Previous studies based on clinical data showed the renal function was not significantly affected, but morphological change of the renal artery ostium was observed due to presence of suprarenal stent wires [9]. Liffman et al in their experimental study using computational fluid dynamics analysis concluded that no significant reduction of renal blood flow was observed when the renal artery ostia (independent of the diameter of renal artery ostia, 3 mm vs 7 mm; or the number of stent wires, single vs multiple) were crossed by stent wires [15]. Our results are consistent to their findings to some extent. Our analysis shows that reduction of flow velocity was independent of the diameter of renal ostium and the number of stent wires. However, our results demonstrated findings different from others as the type of stent struts encroaching the renal ostium and stent wire thickness determine the renal blood flow, with single wire centrally crossing producing more than 20% reduction of flow velocity.

Since it is possible for the blood material to adhere to the wires and thus may affect the flow of blood into the renal artery. This was confirmed by previous experimental study showing that small bits of materials were deposited onto the wire, leading to the increase of cross-sectional area of the stent wire [15]. Thus, we simulated a wire thickness of 1.0 and 2.0 mm in our study to reflect this situation.

Studies using computer-based models have been focused on relationship between implanted (or simulated) stent grafts and hemodynamic changes, as well as stent migration and risk of rupture [16-18]. However, research on the interference of stent wires with renal artery ostium or renal blood flow is scarce. While mid- and long-term results of suprarenal fixation of stent grafts seem satisfactory [7, 8], the long-term safety of suprarenal stent grafts is still not fully understood. This is mainly because of the unknown effect of suprarenal stent wires on renal artery ostium from a long-term point of view. Image visualizations can only identify appearance or configuration changes of the renal artery ostium resulting from the stent wires crossing or coverage, but fail to present information on flow analysis. Our previous *in vitro* phantom study concluded that the cross-sectional area reduction of the renal artery ostium was determined by the wire thickness and number of stent wires crossing the ostium [19]. When the actual wire thickness of 0.4 mm was taken into account in the situation of stent strut crossing the renal ostium, the cross-sectional area reduction was found to be less than 17%. However, the reduction of the cross-sectional area of the renal ostium is significantly higher in the presence of multiple thicker stent wires (wire diameter between 0.98 and 1.3 mm), resulting in a reduction percentage ranging from 26% to 46.7% [19]. This phenomenon was also observed in our study indicating the decisive role of stent wire thickness. Consequently, this is an important issue that should be considered when dealing with the situation of thicker stent wires crossing the renal ostium.

Based on our results of flow analysis, we suggest vascular surgeons should pay special attention to follow-up patients presented with a single stent wire crossing the renal artery ostium centrally with potentially thicker diameters. Recommendations for follow-up of these patients include monitoring of renal function at regular periods to ensure the adequate perfusion to the renal arteries covered by the stent struts; change of treatment or follow-up procedures based on flow analysis, e.g. prophylactic antiplatelet may be considered to reduce the possibility of adhesions forming upon stent wires due to increased flow turbulence.

The wall shear stress at the renal arteries was found to decrease significantly following suprarenal stent grafting, and this should arise clinical awareness, as low wall shear stress is associated with neointimal hyperplasia in either bypass graft or stent [20]. Thus, a low shear stress could lead to reduction of the cross-sectional area of renal ostium owing to presence of stent wires (because of formation of neointimal hyperplasia on the stent surface). It has been reported that augmentation of wall shear stress is accompanied by a local reduction in neointimal hyperplasia [21]. Another potential risk of a low shear stress is the formation of artery plaque or atherosclerosis in the aortic branches [22]. Therefore, from a clinical point of view, hemodynamic analysis of the interference of stent struts with renal arteries is important for understanding the long-term safety of the suprarenal stent grafting, although this needs further studies to confirm it.

Despite the realistic models used in our study, there are some limitations which exist in our study. First, the aorta models were rigid rather than elastic. In normal physiological situation, the artery wall moves with cardiac cycles. However, we believe our results are valid and accurate since the flow analysis was performed using a fluid-structure interaction. Second, only two cases were selected in this study, which is another limitation. Although we tested variable configurations of the stent struts crossing the renal artery ostium, not all of the four types of configuration were simulated in these two patients. Further studies composed of more patients with different aortic geometry (including different ostial diameters with variable stent struts crossing) should be performed so as to draw a robust conclusion.

In conclusion, our preliminary study using FSI analysis to analyze the hemodynamic changes in patients with AAA treated with suprarenal stent grafts demonstrates that the effect of stent wires on the renal blood flow was dependent on the thickness of a stent wire and the type of stent wire crossing. A single wire crossing the renal ostium centrally resulted in up to nearly 30% reduction of flow velocity to the renal arteries. When the stent wire thickness is simulated at 1.0 mm and 2.0 mm, up to 20% reduction of flow velocity was noticed in more than 60% of the tested aorta models. Our results are considered valuable for improving understanding of the long-term outcomes of suprarenal fixation of stent grafts.

Table 1 Measurements of the length of renal artery and distance between entry point of abdominal aorta to the renal artery in two sample patients

Sample patients	**Length of renal artery (mm)**				**Distance between aorta and renal artery (mm)**			
	Pre-stent grafting		**Post-stent grafting**		**Pre-stent grafting**		**Post-stent grafting**	
	LRA	RRA	LRA	RRA	LRA	RRA	LRA	RRA
Patient 1	19.5	27.1	18	12.3	19.5	27.1	35.3	41.2
Patient 2	26.5	20.5	21.5	27	46.6	41.6	62.8	57.7

LRA-left renal artery, RRA-right renal artery

Table 2 Calculation of flow velocity (peak systolic at 0.225 s) to the renal arteries with suprarenal stent struts crossing the renal artery ostium

Sample patients/ renal arteries		**Type of configurations**	**Flow velocity without a stent wire crossing (m/s)**	**Flow velocity calculated with different stent wire thickness (m/s)**		
				0.4 mm	**1.0 mm**	**2.0 mm**
Patient 1	LRA	Single wire peripherally crossing	0.992	1.042	0.757	0.813
	RRA	Two wires peripherally crossing	1.064	1.045	0.926	0.860
Patient 2	LRA	V-shaped wires crossing	0.953	0.905	0.899	0.837
	RRA	Single wire centrally crossing	0.294	0.232	0.211	0.209

LRA-left renal artery, RRA-right renal artery

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Figure legends

Figure 1. Diagrams of different types of stent wires crossing the renal artery ostium, (a) single wire centrally crossing, (b) single wire peripherally crossing, (c) V-shaped wire centrally crossing and (d) multiple wires peripherally crossing.

Figure 2. Realistic CAD AAA models in patient 1 pre-(A) and post-stent grafting (B).

Figure 3 shows the mesh models in patient 2. (A) and (C) are the blood wall meshes in pre-and post-stent grafting, while (B) and (D) are the blood flow meshes in pre-and post-stent grafting.

Figure 4 shows meshing models of the stent struts with a diameter of 0.4 mm, 1.0 mm and 2.0 mm, repsectively (A-C).

Figure 5A demonstraes flow pulsatile in different cardiac cycles at the abdominal aorta, while Fig 5B shows the time-dependent pressure in different cardiac cycles at the aortic branches.

Figure 6. A complete cardiac cycle was applied to the renal arteries for flow analysis in the simulated aorta models.

Figure 7. Hemodynamic effect of 4 types of stent wires crossing the renal artery ostium with a wire thickness of 0.4 mm, 1.0 mm and 2.0 mm on the renal blood flow calculated at the peak systolic phase (t = 0.225s). Figure 7A is the flow analysis in patient 1 without presence of stent wires, while Fig 7B-D in the same patient with a wire thickness of 0.4 mm, 1.0 mm and 2.0 mm shows the flow analysis at the right renal artery with two wires crossing peripherally, and left renal artery with a single wire crossing peripherally. Figure 7 E is the flow analysis in patient 2 without stent

crossing, while Fig 7F shows a singel wire centrally crossing the right renal artery and V-shaped crossing the left renal artery with a wire thickness of 0.4 mm.

Figure 8 demonstrates flow analysis of wall pressure at the renal arteries in patient 1. The wall pressure was found to increased slightly in the presence of stent wires, which is apprent when the wire thickness reaches 1.0 mm and 2.0 mm (Fig 8 C, D) when compared to that observed in a wire thickness of 0.4 mm (Fig 8B) and non-wire crossing (Fig 8A).

Figure 9. Wall shear stress at the renal arteries was noticed to decreased significanly when the stent wires crossed the renal artery ostia, especially apparent in the presence of stent wires with a diameter of 1.0 mm and 2.0, as shown in Fig 9 C and D, compared to that observed with a wire thickness of 0.4 mm (Fig 9B) and non-wire crossing (Fig 9A). The types of stent wire crossing in Figure 8 and 9 are a single wire crossing the left renal ostium peripherally and two wires crossing the right renal ostium peripherally.