IMPROVEMENT OF HAEMODYNAMIC STENT STRUT CONFIGURATION FOR PATENT DUCTUS ARTERIOSUS THROUGH COMPUTATIONAL MODELLING

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To my beloved Ayah, Mak, Abah, Mak Labu, my supportive wife Norsa'adah, my children Muhammad Hadif and Muhammad Hafiy and my siblings Mashitah, Aden, Firdaus and Asma Husna and my family

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ABSTRACT

Currently, the treatment of *Patent Ductus Arteriosus* (PDA) by the implantation of coronary stent has resulted in severe hemodynamic complications. There is thus a need to customize and improve current stent geometry specific to PDA to overcome this problem. Computational Fluid Dynamics (CFD) approaches, verified by an experimental technique are used to analyze current stent strut configurations. Statistical analysis is used to rank the parameter performance and to obtain the best stent configuration. The most favorable configuration is then used to design new stent strut configuration specific for PDA. In the analysis of the new stent design, CFD results show low possibility of re-stenosis process due to thrombosis formation, inflammation, and neo-intimal hyperplasia. Furthermore, comprehensive CFD analysis by solving fluid-structure interaction (FSI) cases has produced an optimum stent strut configuration that is structurally sound. The strength of stent strut configuration due to hemodynamic effect is analyzed through the Von Misses stress distribution. The results show that the new improved design of stent strut configuration has excellent hemodynamic performance. Finally, the new stent design is predicted to be able to overcome hemodynamic complications and stent structural failure when applied specifically to PDA.

ABSTRAK

Rawatan implantasi *stent* koronari pada *Patent Ductus Arteriosus (PDA)* telah menyebabkan komplikasi hemodinamik yang ketara. Oleh yang demikian, penambahbaikan kepada bentuk *stent* sedia ada perlu dilaksanakan terutamanya untuk kegunaan *PDA*. Dalam kajian ini, penambahbaikan reka bentuk *stent* koronari sedia ada untuk kesesuaian pemasangan di *PDA* telah dapat diimplementasikan. Dinamik Bendalir Perkomputeran *(CFD)* turut dibuktikan dengan menggunakan teknik eksperimen dengan menganalisis konfigurasi *stent* sedia ada. Analisis statistik digunakan untuk menilai prestasi setiap parameter *stent* dan untuk mendapat konfigurasi *stent* yang terbaik. Konfigurasi yang terbaik kemudiannya digunakan untuk mereka bentuk konfigurasi *stent* yang baru khusus untuk kegunaan *PDA*. Dalam analisis reka bentuk *stent* yang baru, hasil analisis *CFD* menunjukkan proses *re-stenosis* yang disebabkan oleh pembentukan *trombosis*, keradangan, dan *neo-intimal hyperplasia* adalah rendah. Selain itu, hasil analisis *CFD* yang menyeluruh dengan menyelesaikan interaksi struktur-bendalir *(FSI)* telah membuktikan struktur konfigurasi *stent* adalah kukuh. Kekuatan konfigurasi *stent* disebabkan oleh kesan hemodinamik telah dikenal pasti melalui analisis agihan tegasan *von Misses*. Hasil kajian menunjukkan bahawa reka bentuk *stent* yang diubah suai ini mempunyai prestasi hemodinamik yang sangat baik. Akhir sekali, reka bentuk *stent* baru ini dijangka dapat mengatasi komplikasi hemodinamik dan juga kegagalan struktur *stent* apabila diguna pakai secara khusus dalam *PDA*.

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LIST OF ABBREVIATIONS

BMS	-	Bare metallic stent
CFD	-	Computational Fluid Dynamics
CHD	-	Congenital Heart Disease
CCD	-	Charged couple device
CO	-	Cardiac ouput
DA	-	Ductus Arteriosus
DES	-	Drug Eluting Stent
FEM	-	Finite Element Method
FSI	-	Fluid Structure Interaction
FSP	-	Flow separation time
IJN	-	Institut Jantung Negara
LVOT	-	Left ventricular outflow tract
MAP	-	Mean arterial pressure
mBT	-	Modified Blalock-Taussig
MOSI	-	Modified oscillatory shear index
NIH	-	Neointimal hyperplasia
OSI	-	Oscillatory shear index
PAIVS	-	Pulmonary Atresia with intact ventricular septal
PDA	-	Patent Ductus Arteriosus
PGE1	-	Prolonged prostaglandin E1
RRT	-	Relative residence time
RVOT	-	Right ventricular outflow tract
st	-	Stroke volume
TAWSS	-	Time-averaged wall shear stress
TAWSSG	-	Time-averaged wall shear stress gradient
TGA	-	Transposition of Great Arteries
TOF	-	Tetralogy of Fallot

LIST OF SYMBOLS

E - Young modulus

Re - Reynolds number

I/D_s - Height of void area

V/L_s - Width of void area

α - Angle AB

β - Angle AC

v - Poisson’s ratio

ρ - Fluid density

τ - Wall shear stress

μ - Viscosity coefficient

ϕ - Faced-averaged variable

σ_y - Yield stress

$\boldsymbol{\Delta}$ - Vector gradient operator

$\boldsymbol{V_F}$ - Velocity vector

Γ - Boundary

$\boldsymbol{\ddot{u}_s}$ - Local acceleration of the solid

$\boldsymbol{f_F^B}$ - body force per unit volume

$\boldsymbol{\sigma_s}$ - Solid stress

$\boldsymbol{\sigma_F}$ - Fluid stress

CHAPTER 1

INTRODUCTION

The implantation of thin wire meshes called stent in Ductus Arteriosus (DA) has become a viable alternative treatment for neonates who have been diagnosed with Cyanotic Congenital Heart Disease. The stent is temporarily implanted in the DA region the so-called patent ductus arteriosus (PDA) within 6 to 12 months or until the neonate has gained sufficient weight to undergo the surgical repair for palliative over conduit surgery or first stage cavopulmonary anastomosis. Between 2001 and 2003, approximately 8.9 percent all patients who underwent the PDA stenting procedures were deemed unsuccessful as reported by the National Heart Institute of Malaysia (IJN) [1]. However, rapid advancement of interventional trans-catheter stenting technique is able to reduce mortality and morbidity in neonates [2]. From 2010 to 2011, PDA stenting procedure were successfully implemented on 29 neonates aged less than three months based on data reported by the Department of Pediatrics, National Heart Institute (IJN) of Malaysia.

Maintaining the patency of DA with metallic-based coronary stent was applied as a novel approach, but earlier results have been discouraging [1, 3, 4]. This is due to the difficulty of pulmonary arterioplasty during definitive repairs with less than satisfactory results when the metallic stent is densely embedded into the fibrotic tissue [5]. The complications after the PDA invasive technique such as re-stenosis, acute stent thrombosis, and stent embolization have inspired researchers to develop new and improved stent technology. Previous researchers had reported that the stent strut configurations had a major influence on the process of re-stenosis, especially on the formation of thrombosis [5, 6, 7, 8, 9]. Thus, the stent strut configurations are required to be studied, simulated, and analyzed in detail in order to find some degree of strut improvement due to hemodynamic variables.

The hemodynamic stent performances are predicted based on the hemodynamic variables via computational modeling. Recently, stented DA model can be simulated near the vessel environment due to the advancement and improvement of computing ability and performance. Both computational fluid dynamic (CFD) and fluid-structure interaction (FSI) methods are used and proven by many researchers [5, 6, 8, 9, 10] to predict the hemodynamic stent performance of altered hemodynamic variables. Hence, computational modeling is suitable to be utilized to predict the risk of re-stenosis based on the hemodynamic stent impact on the arterial PDA.

This study proposes a detailed analysis and assessment via statistical data distributions to predict the favorable hemodynamic stents performances among the stents. Three different studies are conducted to pre-clinically assess the stent impact on the arterial PDA stenting. This study begins by comparing the hemodynamic variable effects on eight different types of commercial stent strut configurations. The stents represent both open and closed cell stents implying different response in hemodynamic variables. The hemodynamic variables considered in this study include Time-averaged Wall Shear Stress (TAWSS), Time-averaged low Wall Shear Stress ($\text{TAWSS}_{\text{low}}$), Time-averaged Wall Shear Stress gradient (TAWSSG), Time-averaged Wall Shear Stress angle gradient (TAWSSAG), oscillating shear index (OSI), and relative residence time (RRT). These hemodynamic variables are adopted to predict the best hemodynamic stent performances through the implementation of scoring systems. The implementation of a scoring system to determine the favorable hemodynamic stent performances is then discussed in detail.

In the second study, modified parametric stent strut configurations are modeled and simulated using CFD to predict the hemodynamic effects on the arterial stented PDA. The stent modifications are made based on the hemodynamic results obtained from the simulation of commercial stent strut configurations. The parametric stent models differ in the number of unit cell stents, thickness, and width of strut configurations. The hemodynamic performances of modified strut configuration are then compared with the modified stents to find the best stent through the highest score.

In the third study, computational modelling via fluid-structure interactions (FSI) is performed to predict the hemodynamic effect on the stented PDA. The FSI modeling gives important information related to the stent displacement and the maximum stress exerted on the luminal surfaces, which cannot be obtained from rigid wall simulation. The distinctions of the luminal surface area between FSI and rigid wall imply that the FSI method has the ability to predict nearer to the real vessel environment as compared to rigid wall simulation. The analysis of stress exerted on the stent surfaces is calculated through the von Misses stress that can predict structural stent failure due to hemodynamic effects. Thus, this study aims to predict the hemodynamic stents performances by means of CFD and FSI to reduce the development of re-stenosis.

1.1 Problem Statement

The increase in the rate of re-stenosis a few weeks after stent implantation was of concern and normally depends on various factors including stent strut configurations which alter the hemodynamic variables [5]. Four key processes can explain the process of re-stenosis: thrombus formation, arterial inflammation, neo-intimal hyperplasia (NIH) and remodeling [11]. These processes are triggered by the stimulus from the injury incurred after the stenting procedure. The excessive growth of cell proliferation from the NIH process caused blockage of the arterial wall, thus requiring another stenting procedure. However, this subsequent stent implantation may cause a more severe complication called in-stent restenosis.

1.2 Significance of the Study

Changes of stent strut parameters such as increasing the spacing between strut and strut, decreasing the strut width, and sometimes fewer strut-strut intersections have a significant effect on reducing the re-stenosis rate [12]. This may be due to a different hemodynamic effects on blood borne and arterial wall cells after the implantation of various stent configurations. Thus, stent geometry has become highly significant to be studied and investigated in detail in order to improve the hemodynamic stents performances.

1.3 Objectives

The objectives of this project are:

1. To establish the hemodynamic stent performances due to the effect of existing strut configuration differences by altering hemodynamic variables.

2. To improve and modify stent strut configuration geometry parameterizations to obtain desired strut configuration
3. To quantify the hemodynamic effects on the stent structural in predicting the possibility of structural failure.

1.4 Scope

1. Stents are selected among the commercially available coronary stents.
2. The effects of hemodynamic variables in stent geometry are obtained from the CFD and FSI only.
3. Data establishment on hemodynamic stents performances is based on simplified DA models.
4. The experimental work is validated with the results of numerical simulation.

right pulmonary artery, carotid artery, brachiocephalic artery and subclavian artery to obtain better understanding in improving the geometry of stent strut configuration.

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