

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 Mises 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 output
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
$l/D_s$	-	Height of void area
$VL_s$	-	Width of void area
$\alpha$	-	Angle AB
$\beta$	-	Angle AC
$\nu$	-	Poisson's ratio
$\rho$	-	Fluid density
$\tau$	-	Wall shear stress
$\mu$	-	Viscosity coefficient
$\phi$	-	Faced-averaged variable
$\sigma_y$	-	Yield stress
$\Delta$	-	Vector gradient operator
$V_F$	-	Velocity vector
$\Gamma$	-	Boundary
$\ddot{u}_s$	-	Local acceleration of the solid
$f_F^B$	-	body force per unit volume
$\sigma_s$	-	Solid stress
$\sigma_F$	-	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 (TAWSS<sub>low</sub>), 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 Mises 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.

## REFERENCES

1. Alwi, M., Choo, K. K., Latiff, H. A., Kandavello, G., Samion, H. and Mulyadi, M. D. Initial results and medium-term follow-up of stent implantation of patent ductus arteriosus in duct-dependent pulmonary circulation. *Journal of the American College of Cardiology*, 2004. 44(2): 438–45. ISSN 0735-1097. doi: 10.1016/j.jacc.2004.03.066. URL <http://www.ncbi.nlm.nih.gov/pubmed/15261945>.
2. Alwi, M. Stenting the ductus arteriosus: Case selection, technique and possible complications. *Annals of pediatric cardiology*, 2008. 1(1): 38–45. ISSN 0974-5149. doi:10.4103/0974-2069.41054. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2840730&tool=pmcentrez&rendertype=abstract>.
3. Tamisier, D., Vouhé, P. R., Vernant, F., Lecá, F., Massot, C. and Neveux, J. Y. Modified Blalock-Taussig shunts: results in infants less than 3 months of age. *The Annals of thoracic surgery*, 1990. 49(5): 797–801. ISSN 00034975. doi: 10.1016/0003-4975(90)90026-3.
4. Sivakumar, K., Shivaprakasha, K., Rao, S. G. and Kumar, R. K. Operative outcome and intermediate term follow-up of neonatal Blalock-Taussig shunts. *Indian heart journal*. 53(1): 66–70. ISSN 0019-4832. URL <http://www.ncbi.nlm.nih.gov/pubmed/11456144>.
5. Alwi, M. and Mood, M. C. Stenting of Lesions in Patent Ductus Arteriosus with Duct-Dependent Pulmonary Blood Flow. Focus on Case Selection, Techniques and Outcome, 2013. doi:10.1016/j.iccl.2012.09.011.
6. Alwi, M., Choo, K.-K., Radzi, N. a. M., Samion, H., Pau, K.-K. and Hew, C.-C. Concomitant stenting of the patent ductus arteriosus and radiofrequency valvotomy in pulmonary atresia with intact ventricular septum and intermediate right ventricle: early in-hospital and medium-term outcomes. *The Journal of thoracic and cardiovascular surgery*, 2011. 141(6): 1355–61. ISSN 1097-685X. doi:10.1016/j.jtcvs.2010.08.085. URL <http://www.ncbi.nlm.nih.gov/pubmed/21227471>.
7. Michel-Behnke, I., Akinturk, H., Schranz, D., Gibbs, J. L., Blackburn, M. E.,

- Wren, C., Hamilton, J. L. and Watterson, K. Fate of the Stented Arterial Duct Response. *Circulation*, 2000. 102(22): e178–e178. ISSN 0009-7322. doi: 10.1161/01.CIR.102.22.e178. URL <http://circ.ahajournals.org/cgi/doi/10.1161/01.CIR.102.22.e178>.
8. Gewillig, M., Boshoff, D. E., Dens, J., Mertens, L. and Benson, L. N. Stenting the Neonatal Arterial Duct in Duct-Dependent Pulmonary Circulation: New Techniques, Better Results. *Journal of the American College of Cardiology*, 2004. 43(1): 107–112. ISSN 07351097. doi:10.1016/j.jacc.2003.08.029.
  9. Gibbs, J. L., Uzun, O., Blackburn, M. E., Wren, C., Hamilton, J. R. and Watterson, K. G. Fate of the stented arterial duct. *Circulation*, 1999. 99(20): 2621–2625. ISSN 0009-7322. doi:10.1161/01.CIR.99.20.2621.
  10. Schneider, M., Zartner, P., Sidiropoulos, a., Konertz, W. and Hausdorf, G. Stent implantation of the arterial duct in newborns with duct-dependent circulation. *European heart journal*, 1998. 19(9): 1401–9. ISSN 0195-668X. URL <http://www.ncbi.nlm.nih.gov/pubmed/9792267>.
  11. Schneider, D. J. The patent ductus arteriosus in term infants, children, and adults. *Seminars in perinatology*, 2012. 36(2): 146–153. ISSN 1558-075X. doi:10.1053/j.semperi.2011.09.025. URL <http://www.ncbi.nlm.nih.gov/pubmed/22414886>.
  12. Setchi, A., Mestel, a. J., Siggers, J. H., Parker, K. H., Tan, M. W. and Wong, K. Mathematical model of flow through the patent ductus arteriosus. *Journal of mathematical biology*, 2012. ISSN 1432-1416. doi: 10.1007/s00285-012-0596-8. URL <http://www.ncbi.nlm.nih.gov/pubmed/23053537>.
  13. Pennati, G., Migliavacca, F., Dubini, G. and Bove, E. L. Modeling of systemic-to-pulmonary shunts in newborns with a univentricular circulation: State of the art and future directions. *Progress in Pediatric Cardiology*, 2010. 30(1-2): 23–29. ISSN 10589813. doi:10.1016/j.ppedcard.2010.09.004. URL <http://linkinghub.elsevier.com/retrieve/pii/S1058981310000780>.
  14. Santoro, G., Capozzi, G., Caianiello, G., Palladino, M. T., Marrone, C., Farina, G., Russo, M. G. and Calabrò, R. Pulmonary artery growth after palliation of congenital heart disease with duct-dependent pulmonary circulation: arterial duct stenting versus surgical shunt. *Journal of the American College of Cardiology*, 2009. 54(23): 2180–6. ISSN 1558-3597. doi:10.1016/j.jacc.2009.07.043. URL <http://www.ncbi.nlm.nih.gov/pubmed/19942090>.

15. Michel-Behnke, I., Akintuerk, H., Thul, J., Bauer, J., Hagel, K.-J. and Schranz, D. Stent implantation in the ductus arteriosus for pulmonary blood supply in congenital heart disease. *Catheterization and cardiovascular interventions : official journal of the Society for Cardiac Angiography & Interventions*, 2004. 61(2): 242–52. ISSN 1522-1946. doi:10.1002/ccd.10766. URL <http://www.ncbi.nlm.nih.gov/pubmed/14755821>.
16. Feltes, T. F., Bacha, E., Beekman, R. H., Cheatham, J. P., Feinstein, J. A., Gomes, A. S., Hijazi, Z. M., Ing, F. F., de Moor, M., Morrow, W. R., Mullins, C. E., Taubert, K. A. and Zahn, E. M. Indications for cardiac catheterization and intervention in pediatric cardiac disease: a scientific statement from the American Heart Association. *Circulation*, 2011. 123(22): 2607–52. ISSN 1524-4539. doi:10.1161/CIR.0b013e31821b1f10. URL <http://circ.ahajournals.org/content/123/22/2607>.
17. Armstrong, E. J., Feldman, D. N., Wang, T. Y., Kaltenbach, L. A., Yeo, K. K., Wong, S. C., Spertus, J., Shaw, R. E., Minutello, R. M., Moussa, I., Ho, K. K. L., Rogers, J. H. and Shunk, K. A. Clinical presentation, management, and outcomes of angiographically documented early, late, and very late stent thrombosis. *JACC: Cardiovascular Interventions*, 2012. 5(2): 131–140. ISSN 19368798. doi:10.1016/j.jcin.2011.10.013.
18. Hussain, A., Al-zharani, S., Muhammed, A. A., Al-ata, J. and Galal, O. M. Midterm outcome of stent dilatation of patent ductus arteriosus in ductal-dependent pulmonary circulation. *Congenital Heart Disease*, 2008. 3(4): 241–249. ISSN 1747079X. doi:10.1111/j.1747-0803.2008.00197.x.
19. Odemis, E., Haydin, S., Guzeltas, A., Ozyilmaz, I., Bilici, M. and Bakir, I. Stent implantation in the arterial duct of the newborn with duct-dependent pulmonary circulation: single centre experience from Turkey. *European journal of cardio-thoracic surgery : official journal of the European Association for Cardio-thoracic Surgery*, 2012. 42(1): 57–60. ISSN 1873-734X. doi:10.1093/ejcts/ezr258. URL <http://www.ncbi.nlm.nih.gov/pubmed/22290915>.
20. Schranz, D., Zartner, P., Michel-Behnke, I. and Akintürk, H. Bioabsorbable metal stents for percutaneous treatment of critical recoarctation of the aorta in a newborn. *Catheterization and cardiovascular interventions : official journal of the Society for Cardiac Angiography & Interventions*, 2006. 67(5): 671–3. ISSN 1522-1946. doi:10.1002/ccd.20756. URL <http://www.ncbi.nlm.nih.gov/pubmed/16575923>.
21. McMahon, C. J., Oslizlok, P. and Walsh, K. P. Early restenosis following

- biodegradable stent implantation in an aortopulmonary collateral of a patient with pulmonary atresia and hypoplastic pulmonary arteries. *Catheterization and cardiovascular interventions : official journal of the Society for Cardiac Angiography & Interventions*, 2007. 69(5): 735–8. ISSN 1522-1946. doi:10.1002/ccd.21091. URL <http://www.ncbi.nlm.nih.gov/pubmed/17330269>.
22. Gundert, T. J., Marsden, A. L., Yang, W. and LaDisa, J. F. Optimization of cardiovascular stent design using computational fluid dynamics. *Journal of biomechanical engineering*, 2012. 134(1): 011002. ISSN 1528-8951. doi:10.1115/1.4005542. URL <http://www.ncbi.nlm.nih.gov/pubmed/22482657>.
23. Taib, I., Kadir, M. R. A., Azis, M. H. S. A., Md Khudzari, A. Z. and Osman, K. Analysis of Hemodynamic Differences for Stenting Patent Ductus Arteriosus. *Journal of Medical Imaging and Health Informatics*, 2013. 3(4): 555–560. ISSN 21567018. doi:10.1166/jmih.2013.1197. URL <http://openurl.ingenta.com/content/xref?genre=article&issn=2156-7018&volume=3&issue=4&spage=555>.
24. Duraiswamy, N., Schoepfoerster, R. T. and Moore, J. E. Comparison of near-wall hemodynamic parameters in stented artery models. *Journal of biomechanical engineering*, 2009. 131(6): 061006. ISSN 01480731. doi:10.1115/1.3118764.
25. Murphy, J. and Boyle, F. Predicting neointimal hyperplasia in stented arteries using time-dependant computational fluid dynamics: a review. *Computers in biology and medicine*, 2010. 40(4): 408–18. ISSN 1879-0534. doi:10.1016/j.compbiomed.2010.02.005. URL <http://www.ncbi.nlm.nih.gov/pubmed/20211464>.
26. Pant, S., Bressloff, N. W., Forrester, A. I. J. and Curzen, N. The influence of strut-connectors in stented vessels: a comparison of pulsatile flow through five coronary stents. *Annals of biomedical engineering*, 2010. 38(5): 1893–907. ISSN 1573-9686. doi:10.1007/s10439-010-9962-0. URL <http://www.ncbi.nlm.nih.gov/pubmed/20177782>.
27. Pache, J., Kastrati, A., Mehilli, J., Schühlen, H., Dotzer, F., Hausleiter, J., Fleckenstein, M., Neuman, F. J., Sattelberger, U., Schmitt, C., Müller, M., Dirschinger, J. and Schömig, A. Intracoronary stenting and angiographic results: Strut thickness effect on restenosis outcome (ISAR-STEREO-2) trial. *Journal of the American College of Cardiology*, 2003. 41(8): 1283–1288. ISSN 07351097. doi:10.1016/S0735-1097(03)00119-0.



28. Mauri, L., Silbaugh, T. S., Garg, P., Wolf, R. E., Zelevinsky, K., Lovett, A., Varma, M. R., Zhou, Z. and Normand, S.-L. T. Drug-eluting or bare-metal stents for acute myocardial infarction. *The New England journal of medicine*, 2008. 359(13): 1330–1342. ISSN 1533-4406. doi:10.1056/NEJMoa0801485.
29. Gundert, T. J., Marsden, A. L., Yang, W., Marks, D. S. and LaDisa, J. F. Identification of hemodynamically optimal coronary stent designs based on vessel caliber. *IEEE transactions on bio-medical engineering*, 2012. 59(7): 1992–2002. ISSN 1558-2531. doi:10.1109/TBME.2012.2196275. URL <http://www.ncbi.nlm.nih.gov/pubmed/22547450>.
30. Wernick, M. H., Jeremias, A. and Carrozza, J. P. Drug-eluting stents and stent thrombosis: a cause for concern? *Coronary artery disease*, 2006. 17(8): 661–665. ISSN 0954-6928. doi:10.1097/MCA.0b013e32801122b1.
31. Camenzind, E., Steg, P. G. and Wijns, W. A Cause for Concern. *Circulation*, 2007. 115(11): 1440–1455. ISSN 0009-7322. doi:10.1161/CIRCULATIONAHA.106.666800. URL <http://www.ncbi.nlm.nih.gov/pubmed/17344324>.
32. Kono, K. and Terada, T. Hemodynamics of 8 different configurations of stenting for bifurcation aneurysms. *American Journal of Neuroradiology*, 2013. 34(10): 1980–1986. ISSN 01956108. doi:10.3174/ajnr.A3479.
33. Babiker, M. H., Gonzalez, L. F., Ryan, J., Albuquerque, F., Collins, D., Elvikis, A. and Frakes, D. H. Influence of stent configuration on cerebral aneurysm fluid dynamics. *Journal of biomechanics*, 2012. 45(3): 440–447. ISSN 1873-2380. doi:10.1016/j.jbiomech.2011.12.016. URL <http://www.ncbi.nlm.nih.gov/pubmed/22226405>.
34. Kastrati, A., Mehilli, J., Dirschinger, J., Pache, J., Ulm, K., Schühlen, H., Seyfarth, M., Schmitt, C., Blasini, R., Neumann, F. J. and Schömig, A. Restenosis after coronary placement of various stent types. *American Journal of Cardiology*, 2001. 87(1): 34–39. ISSN 00029149. doi:10.1016/S0002-9149(00)01268-6.
35. Lansky, A. J., Roubin, G. S., O’Shaughnessy, C. D., Moore, P. B., Dean, L. S., Raizner, A. E., Safian, R. D., Zidar, J. P., Kerr, J. L., Popma, J. J., Mehran, R., Kuntz, R. E. and Leon, M. B. *Randomized comparison of GR-II stent and Palmaz-Schatz stent for elective treatment of coronary stenoses*. Technical Report 12. 2000. doi:10.1161/01.CIR.102.12.1364.
36. Baim, D. S., Cutlip, D. E., Midei, M., Linnemeier, T. J., Schreiber, T., Cox, D., Kereiakes, D., Popma, J. J., Robertson, L., Prince, R., Lansky, A. J., Ho,

- K. K. L. and Kuntz, R. E. Final results of a randomized trial comparing the MULTI-LINK stent with the Palmaz-Schatz stent for narrowings in native coronary arteries. *American Journal of Cardiology*, 2001. 87(2): 157–162. ISSN 00029149. doi:10.1016/S0002-9149(00)01308-4.
37. Koskinas, K. C., Chatzizisis, Y. S., Antoniadis, A. P. and Giannoglou, G. D. Role of endothelial shear stress in stent restenosis and thrombosis: pathophysiologic mechanisms and implications for clinical translation. *Journal of the American College of Cardiology*, 2012. 59(15): 1337–49. ISSN 1558-3597. doi:10.1016/j.jacc.2011.10.903. URL <http://www.ncbi.nlm.nih.gov/pubmed/22480478>.
38. Larrabide, I., Radaelli, A. and Frangi, A. Fast virtual stenting with deformable meshes: Application to intracranial aneurysms. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 2008, vol. 5242 LNCS. ISBN 3540859896. ISSN 03029743. 790–797. doi:10.1007/978-3-540-85990-1-95.
39. Duraiswamy, N., Cesar, J. M., Schoepfoerster, R. T. and Moore, J. E. Effects of stent geometry on local flow dynamics and resulting platelet deposition in an in vitro model. *Biorheology*, 2008. 45(5): 547–61. ISSN 0006-355X. URL <http://www.ncbi.nlm.nih.gov/pubmed/19065004>.
40. Pache, J., Kastrati, A., Mehilli, J., Schühlen, H., Dotzer, F., Hausleiter, J., Fleckenstein, M., Neuman, F. J., Sattelberger, U., Schmitt, C., Müller, M., Dirschinger, J. and Schömig, A. Intracoronary stenting and angiographic results: Strut thickness effect on restenosis outcome (ISAR-STEREO-2) trial. *Journal of the American College of Cardiology*, 2003. 41(8): 1283–1288. ISSN 07351097. doi:10.1016/S0735-1097(03)00119-0.
41. Serruys, P. W., Degertekin, M., Tanabe, K., Abizaid, A., Sousa, J. E., Colombo, A., Guagliumi, G., Wijns, W., Lindeboom, W. K., Ligthart, J., de Feyter, P. J. and Morice, M.-C. Intravascular ultrasound findings in the multicenter, randomized, double-blind RAVEL (RAnomized study with the sirolimus-eluting VELOCITY balloon-expandable stent in the treatment of patients with de novo native coronary artery Lesions) trial. *Circulation*, 2002. 106(7): 798–803. ISSN 1524-4539. URL <http://www.ncbi.nlm.nih.gov/pubmed/12176950>.
42. Frank, A. O., Walsh, P. W. and Moore, J. E. Computational fluid dynamics and stent design. *Artificial organs*, 2002. 26(7): 614–21. ISSN 0160-564X. URL <http://www.ncbi.nlm.nih.gov/pubmed/22482657>.
43. LaDisa, J. F., Olson, L. E., Hettrick, D. a., Warltier, D. C., Kersten,

- J. R. and Pagel, P. S. Axial stent strut angle influences wall shear stress after stent implantation: analysis using 3D computational fluid dynamics models of stent foreshortening. *Biomedical engineering online*, 2005. 4: 59. ISSN 1475-925X. doi:10.1186/1475-925X-4-59. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1276824&tool=pmcentrez&rendertype=abstract>.
44. Pekkan, K., Dasi, L. P., Nourparvar, P., Yerneni, S., Tobita, K., Fogel, M. A., Keller, B. and Yoganathan, A. In vitro hemodynamic investigation of the embryonic aortic arch at late gestation. *Journal of Biomechanics*, 2008. 41(8): 1697–1706. ISSN 00219290. doi:10.1016/j.jbiomech.2008.03.013.
45. Briguori, C., Sarais, C., Pagnotta, P., Liistro, F., Montorfano, M., Chieffo, A., Sgura, F., Corvaja, N., Albiero, R., Stankovic, G., Toutoutzas, C., Bonizzoni, E., Di Mario, C. and Colombo, A. In-stent restenosis in small coronary arteries: Impact of strut thickness. *Journal of the American College of Cardiology*, 2002. 40(3): 403–409. URL <http://www.sciencedirect.com/science/article/pii/S0735109702019897>.
46. Hsiao, H.-M., Lee, K.-H., Liao, Y.-C. and Cheng, Y.-C. Cardiovascular stent design and wall shear stress distribution in coronary stented arteries. *Micro & Nano Letters*, 2012. 7(5): 430. ISSN 17500443. doi:10.1049/mnl.2011.0590. URL <http://digital-library.theiet.org/content/journals/10.1049/mnl.2011.0590>.
47. Bakhshali, M. A., Mafi, M. and Daneshvar, S. Mathematical modelling of the patent ductus arteriosus (PDA). *Mathematical and Computer Modelling of Dynamical Systems*, 2013. 19(3): 238–249. ISSN 1387-3954. doi:10.1080/13873954.2012.727187. URL <http://www.tandfonline.com/doi/abs/10.1080/13873954.2012.727187>.
48. Shobayashi, Y., Tanoue, T., Tateshima, S. and Tanishita, K. Mechanical design of an intracranial stent for treating cerebral aneurysms. *Medical engineering & physics*, 2010. 32(9): 1015–24. ISSN 1873-4030. doi:10.1016/j.medengphy.2010.07.002. URL <http://www.ncbi.nlm.nih.gov/pubmed/20675176>.
49. Jiménez, J. M. and Davies, P. F. Hemodynamically driven stent strut design. *Annals of biomedical engineering*, 2009. 37(8): 1483–94. ISSN 1573-9686. doi:10.1007/s10439-009-9719-9. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2819751&tool=pmcentrez&rendertype=abstract>.
50. Li, N., Zhang, H. and Ouyang, H. Shape optimization of coronary artery

- stent based on a parametric model. *Finite Elements in Analysis and Design*, 2009. 45(6-7): 468–475. URL <http://www.sciencedirect.com/science/article/pii/S0168874X0900002X>.
51. Pant, S., Limbert, G., Curzen, N. P. and Bressloff, N. W. Multiobjective design optimisation of coronary stents. *Biomaterials*, 2011. 32(31): 7755–73. ISSN 1878-5905. doi:10.1016/j.biomaterials.2011.07.059. URL <http://www.ncbi.nlm.nih.gov/pubmed/21821283>.
  52. Lally, C., Dolan, F. and Prendergast, P. J. Cardiovascular stent design and vessel stresses: a finite element analysis. *Journal of biomechanics*, 2005. 38(8): 1574–81. ISSN 0021-9290. doi:10.1016/j.jbiomech.2004.07.022. URL <http://www.ncbi.nlm.nih.gov/pubmed/15958213>.
  53. Chiastra, C., Migliavacca, F., Martínez, M. A. and Malvè, M. On the necessity of modelling fluid-structure interaction for stented coronary arteries. *Journal of the Mechanical Behavior of Biomedical Materials*, 2014. 34: 217–230. ISSN 18780180. doi:10.1016/j.jmbbm.2014.02.009.
  54. Coimbatore Selvarasu, N. K. Investigation of the Hemodynamics of Coronary Arteries - Effect of Stenting, 2013. URL <https://vtechworks.lib.vt.edu/handle/10919/50568>.
  55. Faik, I., Mongrain, R., Leask, R. L., Rodes-Cabau, J., Larose, E. and Bertrand, O. Time-dependent 3D simulations of the hemodynamics in a stented coronary artery. *Biomedical materials (Bristol, England)*, 2007. 2(1): S28–S37. ISSN 1748-6041. doi:10.1088/1748-6041/2/1/S05.
  56. Benard, N., Perrault, R. and Coisne, D. Computational approach to estimating the effects of blood properties on changes in intra-stent flow. *Annals of biomedical engineering*, 2006. 34(8): 1259–71. ISSN 0090-6964. doi: 10.1007/s10439-006-9123-7. URL <http://www.ncbi.nlm.nih.gov/pubmed/16799830>.
  57. LaDisa, Jr., J. F., Guler, I., Olson, L. E., Hettrick, D. A., Kersten, J. R., Warltier, D. C. and Pagel, P. S. Three-Dimensional Computational Fluid Dynamics Modeling of Alterations in Coronary Wall Shear Stress Produced by Stent Implantation. *Annals of Biomedical Engineering*, 2003. 31(8): 972–980. ISSN 0090-6964. doi:10.1114/1.1588654. URL <http://link.springer.com/10.1114/1.1588654>.
  58. LaDisa, J. F. Stent design properties and deployment ratio influence indexes of wall shear stress: a three-dimensional computational fluid dynamics investigation within a normal artery. *Journal of Applied Physiology*, 2004.

- 97(1): 424–430. ISSN 8750-7587. doi:10.1152/jappphysiol.01329.2003. URL <http://www.ncbi.nlm.nih.gov/pubmed/14766776>.
59. He, Y., Duraiswamy, N., Frank, A. O. and Moore, J. E. Blood flow in stented arteries: a parametric comparison of strut design patterns in three dimensions. *Journal of biomechanical engineering*, 2005. 127(4): 637–647. ISSN 01480731. doi:10.1115/1.1934122.
60. Balossino, R., Gervaso, F., Migliavacca, F. and Dubini, G. Effects of different stent designs on local hemodynamics in stented arteries. *Journal of biomechanics*, 2008. 41(5): 1053–61. ISSN 0021-9290. doi: 10.1016/j.jbiomech.2007.12.005. URL <http://www.ncbi.nlm.nih.gov/pubmed/18215394>.
61. M.A. Salehi\* and A.Oladzadeh. Three-dimensional Simulation of Blood Flow in Stented Vessels and the Comparison of Wall Shear Stress in Various Stent Plans Using CFD, 2013. URL <http://jnasci.org/wp-content/uploads/2013/12/1076-1084.pdf>.
62. He, Y., Duraiswamy, N., Frank, A. O. and Moore, J. E. Blood flow in stented arteries: a parametric comparison of strut design patterns in three dimensions. *Journal of biomechanical engineering*, 2005. 127(4): 637–47. ISSN 0148-0731. URL <http://www.ncbi.nlm.nih.gov/pubmed/16121534>.
63. Murphy, J. and Boyle, F. Predicting neointimal hyperplasia in stented arteries using time-dependant computational fluid dynamics: A review. *Computers in Biology and Medicine*, 2010. 40(4): 408–418. URL <http://www.sciencedirect.com/science/article/pii/S001048251000020X>.
64. LaDisa Jr., J. F., Olson, L. E., Hettrick, D. A., Warltier, D. C., Kersten, J. R. and Pagel, P. S. Axial stent strut angle influences wall shear stress after stent implantation: analysis using 3D computational fluid dynamics models of stent foreshortening. *Biomed Eng Online*, 2005. 4: 59.
65. Khanafer, K. M., Gadhoke, P., Berguer, R. and Bull, J. L. Modeling pulsatile flow in aortic aneurysms: effect of non-Newtonian properties of blood. *Biorheology*, 2006. 43(5): 661–79.
66. Gundert, T. J., Dholakia, R. J., McMahon, D. and LaDisa, J. F. Computational Fluid Dynamics Evaluation of Equivalency in Hemodynamic Alterations Between Driver, Integrity, and Similar Stents Implanted Into an Idealized Coronary Artery. *Journal of Medical Devices*, 2013. 7(1): 011004. ISSN 1932-6181. doi:10.1115/1.4023413. URL

<http://medicaldevices.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4023413>.

67. Pant, S., Bressloff, N. W. and Limbert, G. Geometry parameterization and multidisciplinary constrained optimization of coronary stents. *Biomechanics and modeling in mechanobiology*, 2012. 11(1-2): 61–82. ISSN 1617-7940. doi:10.1007/s10237-011-0293-3. URL <http://www.ncbi.nlm.nih.gov/pubmed/21373889>.
68. Torii, R., Oshima, M., Kobayashi, T., Takagi, K. and Tezduyar, T. E. Computer modeling of cardiovascular fluid structure interactions with the deforming-spatial-domain/stabilized space in time formulation. *Computer Methods in Applied Mechanics and Engineering*, 2006. 195(13-16): 1885–1895. ISSN 00457825. doi:10.1016/j.cma.2005.05.050. URL <http://linkinghub.elsevier.com/retrieve/pii/S0045782505003117>.
69. Chen, H., G. Kassab, F. G., S. De and K, M. M. R. Computational Modeling of Coronary Stents, in *Computational Modeling in Biomechanics. Springer Netherlands*, 2010: 207–220.
70. Govindaraju, S. D. Influence of fluid-structure interaction on wall shear stress in a stented coronary artery model. 2012. URL <http://gradworks.umi.com/35/29/3529986.html>.
71. Alwi, M. Stenting the patent ductus arteriosus in duct-dependent pulmonary circulation: techniques, complications and follow-up issues, 2012. doi:10.2217/fca.12.4.
72. Matsui, H., McCarthy, K. and Ho, S. Morphology of the patent arterial duct: features relevant to treatment. *Images in paediatric cardiology*, 2008. 10(1): 27–38. ISSN 1729-441X. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3232584&tool=pmcentrez&rendertype=abstract>.
73. Miller, M. W., Gordon, S. G., Saunders, A. B., Arsenault, W. G., Meurs, K. M., Lehmkuhl, L. B., Bonagura, J. D. and Fox, P. R. Angiographic classification of patent ductus arteriosus morphology in the dog. *Journal of Veterinary Cardiology*, 2006. 8(2): 109–114. ISSN 17602734. doi:10.1016/j.jvc.2006.07.001.
74. Petrini, L., Migliavacca, F., Auricchio, F. and Dubini, G. Numerical investigation of the intravascular coronary stent flexibility. *Journal of Biomechanics*, 2004. 37(4): 495–501. URL <http://www.sciencedirect.com/science/article/pii/S0021929003003397>.

75. Sick, P. B., Gelbrich, G., Kalnins, U., Erglis, A., Bonan, R., Aengevaeren, W., Elsner, D., Lauer, B., Woinke, M., Brosteanu, O. and Schuler, G. Comparison of early and late results of a Carbofilm-coated stent versus a pure high-grade stainless steel stent (the Carbostent-Trial). *American Journal of Cardiology*, 2004. 93(11): 1351–1356. ISSN 00029149. doi:10.1016/j.amjcard.2004.02.029.
76. Colombo, A., Stankovic, G. and Moses, J. W. Selection of coronary stents. *Journal of the American College of Cardiology*, 2002. 40(6): 1021–1033. ISSN 07351097. doi:10.1016/S0735-1097(02)02123-X.
77. Martin, D. M. and Boyle, F. J. Drug-eluting stents for coronary artery disease: a review. *Medical engineering & physics*, 2011. 33(2): 148–63. ISSN 1873-4030. doi:10.1016/j.medengphy.2010.10.009. URL <http://www.ncbi.nlm.nih.gov/pubmed/21075668>.
78. Forbes, T. J., Rodriguez-Cruz, E., Amin, Z., Benson, L. N., Fagan, T. E., Hellenbrand, W. E., Latson, L. A., Moore, P., Mullins, C. E. and Vincent, J. A. The Genesis stent: A new low-profile stent for use in infants, children, and adults with congenital heart disease. *Catheterization and Cardiovascular Interventions*, 2003. 59(3): 406–414. ISSN 15221946. doi:10.1002/ccd.10547.
79. Walke, W., Paszenda, Z. and Filipiak, J. Experimental and numerical biomechanical analysis of vascular stent. *Journal of Materials Processing Technology*, 2005. 164-165(0): 1263–1268. URL <http://www.sciencedirect.com/science/article/pii/S0924013605000828>.
80. Kobayashi, T., Tomita, H., Yokozawa, M., Takamuro, M., Hatakeyama, K., Kim, S. H., Ono, Y. and Sakamoto, K. Genesis stent implantation without using a long sheath in two children. *Journal of Cardiology*, 2008. 52(3): 296–299. ISSN 09145087. doi:10.1016/j.jjcc.2008.06.002.
81. Xia, Z., Ju, F. and Sasaki, K. A general finite element analysis method for balloon expandable stents based on repeated unit cell (RUC) model. *Finite Elements in Analysis and Design*, 2007. 43(8): 649–658. URL <http://www.sciencedirect.com/science/article/pii/S0168874X07000054>.
82. Dumoulin, C. and Cochelin, B. Mechanical behaviour modelling of balloon-expandable stents. *Journal of Biomechanics*, 2000. 33(11): 1461–1470. URL <http://www.sciencedirect.com/science/article/pii/S0021929000000981>.

83. McGarry, J. P., O'Donnell, B. P., McHugh, P. E. and McGarry, J. G. Analysis of the mechanical performance of a cardiovascular stent design based on micromechanical modelling. *Computational Materials Science*, 2004. 31(3-4): 421–438. URL <http://www.sciencedirect.com/science/article/pii/S0927025604001570>.
84. Wang, W.-Q., Liang, D.-K., Yang, D.-Z. and Qi, M. Analysis of the transient expansion behavior and design optimization of coronary stents by finite element method. *Journal of Biomechanics*, 2006. 39(1): 21–32. URL <http://www.sciencedirect.com/science/article/pii/S0021929004005378>.
85. Linxia, G., Santra, S., Mericle, R. A. and Kumar, A. V. Finite element analysis of covered microstents. *Journal of Biomechanics*, 2005. 38(6): 1221–1227. URL <http://www.sciencedirect.com/science/article/pii/S0021929004003069>.
86. Kojima, M., Irie, K., Fukuda, T., Arai, F., Hirose, Y. and Negoro, M. The study of flow diversion effects on aneurysm using multiple enterprise stents and two flow diverters. 2012. 7(4): 159–165. doi:10.4103/1793.
87. Miller, M. W., Gordon, S. G., Saunders, A. B., Arsenault, W. G., Meurs, K. M., Lehmkuhl, L. B., Bonagura, J. D. and Fox, P. R. Angiographic classification of patent ductus arteriosus morphology in the dog. *Journal of Veterinary Cardiology*, 2006. 8(2): 109–114. ISSN 17602734. doi: 10.1016/j.jvc.2006.07.001.
88. Henry Y. Chen, G. S. K. *Computational Modeling in Biomechanics*. Dordrecht: Springer Netherlands. 2010. ISBN 978-90-481-3574-5. doi: 10.1007/978-90-481-3575-2. URL <http://www.springerlink.com/index/10.1007/978-90-481-3575-2>.
89. Malek, A. M., Alper, S. L. and Izumo, S. Hemodynamic shear stress and its role in atherosclerosis. *JAMA : the journal of the American Medical Association*, 1999. 282(21): 2035–2042. ISSN 00987484. doi:10.1001/jama.282.21.2035.
90. Toutouzas, K., Colombo, A. and Stefanadis, C. Inflammation and restenosis after percutaneous coronary interventions, 2004. doi:10.1016/j.ehj.2004.06.011.
91. Khanafer, K. M., Bull, J. L., Upchurch Jr, G. R. and Berguer, R. Turbulence Significantly Increases Pressure and Fluid Shear Stress in an Aortic Aneurysm Model under Resting and Exercise Flow Conditions. *Annals of Vascular*



- Surgery*, 2007. 21(1): 67–74. URL <http://www.sciencedirect.com/science/article/pii/S0890509606000148>.
92. Budwig, #160, R., ELGER, D., HOOPER, H., SLIPPY and J. *Steady flow in abdominal aortic aneurysm models*. vol. 115. New York, NY, ETATS-UNIS: American Society of Mechanical Engineers. 1993.
93. Egelhoff, C. J., Budwig, R. S., Elger, D. F., Khraishi, T. A. and Johansen, K. H. Model studies of the flow in abdominal aortic aneurysms during resting and exercise conditions. *Journal of Biomechanics*, 1999. 32(12): 1319–1329. URL <http://www.sciencedirect.com/science/article/pii/S0021929099001347>.
94. Thury, A., Wentzel, J. J., Vinke, R. V. H., Gijzen, F. J. H., Schuurbiers, J. C. H., Krams, R., de Feyter, P. J., Serruys, P. W. and Slager, C. J. Images in cardiovascular medicine. Focal in-stent restenosis near step-up: roles of low and oscillating shear stress? *Circulation*, 2002. 105(23): e185–7. ISSN 1524-4539. URL <http://www.ncbi.nlm.nih.gov/pubmed/12057999>.
95. Martin, D. and Boyle, F. J. Computational structural modelling of coronary stent deployment: a review. *Computer methods in biomechanics and biomedical engineering*, 2011. 14(4): 331–348. ISSN 1025-5842. doi: 10.1080/10255841003766845.
96. Rutherford, R. B. Structural failures in abdominal aortic aneurysm stentgrafts: Threat to durability and challenge to technology, 2004. doi:10.1053/j.semvascsurg.2004.09.009.
97. Carter, A. J. Drug-Eluting Stent Fracture. *Journal of the American College of Cardiology*, 2009. 54(21): 1932–1934. ISSN 07351097. doi:10.1016/j.jacc.2009.07.035. URL <http://www.ncbi.nlm.nih.gov/pubmed/19909873>.