A review of stent’s failure on patent ductus arteriosus

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Abstract. This paper presents a review of stent’s failure on patent ductus arteriosus (PDA). Ductus arteriosus (DA) is a small vessel connecting between two major blood vessels, the aortic arch (AA) and pulmonary artery (PA) that permit blood to bypass the pulmonary circulation. Originally, DA is a normal part of every foetal to allow the exchange of oxygenation blood with maternal blood through placenta. After a few days of birth, the DA usually close, the closure does not occur on some people and lead to the condition known as Patent Ductus arteriosus (PDA) [2]. The purpose of stenting on PDA mainly because of typical lesions such as pulmonary and tricuspid atresia, critical pulmonary stenosis and tetralogy of Fallot. Implantation of stent in PDA is needed for survival in these patients [2, 3]. Tricuspid atresia is a type of congenital heart disease where the valve between the right atrium and right ventricle fails to develop. The pulmonary atresia on the other hand is defect of the pulmonary valve, which is the valve that controls blood flow from the right ventricle to the main pulmonary artery. Pulmonary stenosis is a condition of obstruction to blood flow from the right ventricle to the pulmonary artery. Tetralogy of Fallot is a congenital heart defect. This is a problem with the heart's structure that's present at birth and change the normal flow of blood through the heart. It occurs in about 5 out of every 10,000 babies [3].
Other method to connect the AA and PA by modified Blalock-Taussig (mBT) which an open surgery that cause high morbidity and mortality compare to PDA stenting. Traditionally, mBT surgery is the first treatment option, but due to some factor such as very severe disease high risk patient, very low birth weight, or lack of service's experience, mBT can be limited [4, 5].

**Figure 1.** Finite element mesh for the stent–artery–balloon system [6]

Figure 1 above show the finite element mesh for the stent–artery–balloon system. Normally there are two type of expanding stent inside human artery which are balloon-expanding and self-expanding stent. The wall of an artery consists of three layers. The tunica intima is innermost layer, which is simple squamous epithelium surrounded by a connective tissue basement membrane with elastic fibers. The tunica media is middle layer, which is primarily smooth muscle and is usually the thickest layer. The tunica adventitia is outermost layer, which attaches the vessel to the surrounding tissue. This layer is connective tissue with varying amounts of elastic and collagenous fibers.

**Figure 2.** (a) Location of PDA, (b) Straight tubular vessel DA, (C) Curved vessel DA, (d) Bulging shape DA [7]
Figure 1 show the location of PDA near to human heart. There are straight tubular vessel DA, curved vessel DA and bulging shape duct DA. The opening of DA supply blood flow to the lungs from critical right heart obstructive lesion and also supplies to systemic and parallel circulation from critical left heart lesion. The bidirectional flows exist in DA from mixing of oxygenated and deoxygenated blood.

2. Stent placement on PDA
Patent ductus arteriosus (PDA), one of the most common congenital heart defects (CHD). Some PDA morphology is straight duct while some are too big in diameter, curved or tortuous, tubular, funnel shaped, long and meandering, short or have no length or also known as window duct [8]. This paper only review on straight duct type of PDA. Morphology in this paper refer to the shape, form and structure of patent ductus arteriosus. The selection of stent placement on PDA based on the morphology of PDA. The common size of straight duct PDA varies from 7 to 11mm long and 4 to 5mm in diameter [8]. Table 1 show Patient and Procedural Characteristics on PDA, two types of stents are used and two from three patients are survive.

| Table 1. Patient and Procedural Characteristics on PDA [9] |
|-----------------------------------------------------------|
| **Clinical data**                                         |
| Age, y/sex                                                | 9.7/male   | 3.3/male   | 2.3/male   |
| Weight, kg/height, cm                                     | 24.6/134   | 14/94      | 12.5/88    |
| **Stent data**                                            |
| Number of stents                                          | 1          | 1          | 2          |
| Type of stent                                             | Valéo      | Valéo      | Genesis    |
| Diameter/length, mm                                       | 9×26       | 7×26       | 6×18+7×18  |
| **Follow-up, mo/outcomes**                                |
|                                                           | 8/alive    | 10/alive   | 24 mo/death|

The materials selection for coronary stents preferably consist of criteria such as flexible, supportive, capable of expansion, and biocompatible. The using of material such as metallic based have been used for coronary stents [10]. Ishkritz et al. [11] used two types of materials for finite element analysis (FEA) of stent in PDA which is stainless steel 316L and cobalt–chromium L605 and their parameters showed in Table 2. The most commonly used material for Bare-metal stent (BMS) platforms is 316L stainless-steel, the advantages of using BMS stainless steel are adequate mechanical properties and high corrosion resistance [12]. However, the cobalt–chromium alloy has an excellent radial strength, which allows the development of stents with ultrathin struts while preserved radial force. Other favorable the cobalt–chromium alloy characteristics was adequate radio-opacity and better deliverability [13].

| Table 2. The Material Properties for Stents [11] |
|------------------------------------------------|
| **Material of the stents** | **Density (kg/m³)** | **Young’s Modulus (Mpa)** | **Poisson’s Ratio** | **Yield Strength (σy)** | **Tangent Modulus** |
| Stainless Steel 316L       | 7800               | 193000                | 0.27               | 207                      | 692                 |
| Cobalt-Chromium L605       | 9700               | 243000                | 0.3                | 476                      | 680                 |
Thin-strut stents tend to have lower profiles than thick-strut stents. This lower profile strut lead to less contact between stent and arterial wall surface and decrease the in stent restenosis (ISR). Clinical reports reported that strut thickness may affect restenosis rates [14]. Radial strength describes the external pressure that a stent is able to withstand without incurring 'clinically significant damage', the radial strength of the stent should be enough to support the hemodynamic and arterial wall force. Stents must have sufficient radial strength to treat diseased artery [15]. While the radio-opacity is the advantage of stent visibility and deliverability refer to the flexibility of the stent on deliver phase using catheter. On the deliver phase of stent, the stent is compressed into catheter and deliver through curvy blood vessel to the stent implantation site.

In contrast to BMS material, biodegradable stent offer some advantage. The polymers and metal alloys are example of biodegradable stent. Some advantage of polymers that it could predict the degradation time however having unsatisfied mechanical characteristic while magnesium alloys is the other way around [16]. At some point, for temporary stenting in PDA, biodegradable stent is suitable device compare to BMS stent. Advantage of stent decaying proses poses by degradable stent solved the main concern in pediatric stenting as suitable for baby's growth. The ideal characteristics of a biodegradable stent have been defined as (1) sufficient radial strength to prevent vascular recoil, (2) minimal thrombotic and inflammatory response (3) avoidance of intimal proliferation (4) reabsorption of stent components within months (5) no release of toxic products or embolic material during breakdown and (6) easy processing and sterilization [17].

3. Failure of Stent

Failure of stent on PDA is a key point to address before stent optimization process. The previous work by previous researchers regarding the stent’s failure are reviewed in this section. Mechanical stent failure (MSF) is seldom occasion however the failure is very dangerous [18]. The most common categories are longitudinal stent deformation, stent fracture, stent under expansion and stent recoil [18]. The MSF rate reported that from 136 patients undergoing stent implantation, 17 patients (12.5%) endure mechanical stent failure [19]. From 17 patients, 16 having focal and 1 having in stent restenosis (ISR) [19].

The focal ISR known as lesion that less than 10mm and occur at unscaffolded segment, while diffuse ISR is lesion that more than 10mm [20]. There are three types of diffuse ISR, which are confined to stent margin, beyond stent margin, and total occlusion or have a flow rate 0 [21]. Complete stent fracture occur in one patient (5.9%), partial stent fracture endure by 3 patients (17.6%) while 13 (76.5%) more experienced longitudinal deformation and stent's strut fracture [19].

The stent’s fracture caused by vessel tortuosity, longer stent length, overlapping stenting, calcified and ostial lesions and high deployment pressure while stent’s longitudinal deformation caused by guideliner use, use of post dilatation balloons and multiple stent implantation [18]. The pre and routine post dilation balloon is useful for facilitate optimal stent deployment (SD) and stent optimization (STOP). Pre-dilatation with the correct size and type of balloon will cause less trauma to the vessel than direct stenting [22, 23]. Pre-dilatation also: (1) Increases the rate of successful stent delivery by creating a pathway for the delivery system; (2) May prevent damage to the drug coating during delivery; (3) Can help to estimate lesion length and diameter using the balloon markers; (4) Aids full stent apposition by modifying the lesion before the practitioner places the stent.

The fatigue of stent structure is one of the stent failure. The stent fatigue is the weakening of the stent material and structure caused by repeatedly applied loads. It is localised structural damaged that occurs when stent is subjected to cyclic loading. These loads must be tested before stent are used in blood vessel. Every stent have fatigue limit that define the highest stress that material can withstand for infinite number of cycles without breaking. Marrey et al. [24] mention that fatigue life of 10^8 cycles is required for a 10 year life of stent to design against premature mechanical failure. This approach to fatigue design also used in most other fields of engineering, e.g., in automobile or aerospace applications [24]. According to Marrey et al. [24] the fatigue design using two methodologies which are the traditional stress/strain-life (S-N) approach, and the damage-tolerant or
fracture-mechanics approach. Damage tolerant approaches relying on fracture mechanics based crack growth data have been proposed and successfully applied to larger implant devices such as metallic and pyrolytic carbon mechanical heart valve prostheses [25, 26].

Figure 3. The simulation of estimated location cracks initiation [24]

Figure 3 showed the Finite element methods (FEM) simulation contour of estimated location of cracks initiation. FEM are considered to be an efficient way of testing and improving stent designs to minimize In-stent restenosis (ISR) from biomechanical aspects [27]. The inverse fatigue safety factors (SF) indicate the worst-case fatigue location where fatigue cracks probably initiate. The worst-case fatigue location mean that the location of stent element with the lowest SF or highest inverse fatigue SF. The safety factor means load carrying capacity of structure beyond or under the expected or actual load. The red colour location from the simulation indicate the possible location of structure failure and important for stent structure design optimization.

The investigation of stent’s failure stent also have been done experimentally by Pelton et al, [28]. According to Pelton et al. [28] stent experimental testing is reliable as a stent’s failure test and its results are very important as reference for stent design optimization. The testing specimen, variables, and load generator are controlled following some standardization testing. Figure 4 showed Diamond subcomponent of stent and fixture of cyclic testing. It was designed to determine stent’s pulsatile fatigue properties. The tests were conducted at 30 Hz per ASTM recommendations [28].

Figure 4. (a) Diamond subcomponent of stent (b) Fixture of cyclic testing [28]
A total of 432 subcomponents was tested [28]. This diamond stent’s subcomponent consists of strut length, width and thickness by 8mm, 330μm, and 350μm [28]. The subcomponent were designed by top and bottom holder to provide proper alignment, structural stability, reduction of axial buckling, and secure gripping during laboratory testing [28]. The producing of nitinol test specimens by laser machined, processed at 500°C about 10 min and water quenched [28]. Although experimental subcomponent was scale up geometrically, but the material properties (nitinol) and material machining (laser-machined) was keeping nearly as actual product [28]. The effect of controlling environment during testing, high frequency of stent's subcomponent testing in air resulted the same fatigue reaction as in vivo conditions [29]. The tests were conducted until the stents fractured or achieve 10 million cycles [28].

Figure 5. Strain Amplitude (%) versus Number of cycles [28]

Figure 5 above showed graph of percentage strain amplitude versus number of cycles of experimental stent fatigue failure test. The graph indicate that higher percentage of strain amplitude resulted lower number of cycles and vice versa. The number of cycles represent the stent's life cycle before fatigue failure. The stent's design optimization lifetime could be predicted by referring to the tabulated graph on figure above.

Figure 6. (a) Distribution of equivalent strain (b) Fatigue fracture on bridge tip region [30]
Figure 6 shows the distribution of equivalent strain and fatigue fracture on bridge tip region. Simulation of stents represent the motion of stent when in service and indicate the critical region of stent’s failure. Critical region for equivalent strain show identical with fatigue fracture on bridge tip region. The external work done on an elastic member in causing it to distort from its unstressed state is transformed into strain energy.

The plastic strain energy from to low or high cycle stress can be predicted by simulation contour and failure location of stent can be estimated for further stent optimization. Energy principles in structural mechanics express the relationships between stresses, strains or deformations, displacements, material properties, and external effects in the form of energy or work done by internal and external forces. Since energy is a scalar quantity, these relationships provide convenient and alternative means for formulating the governing equations of deformable bodies in solid mechanics.

4. Conclusion
The stent structure failure by fatigue load have been a major concern for the researcher all over the world. This human implant device is very important for example stenting on patent ductus arteriosus to save patients having cyanotic congenital heart disease (CCHD). PDA stenting safer than open surgery known as modified Blalock-Taussig to treat CCHD. PDA morphology varies such as bulging shape, curve or tortuous, and straight duct, for simplicity this paper reviewed the straight duct stent implantation on PDA. The reviewed of investigation about the fatigue stent failure in this paper are executed by simulation and experiment, however the simulation is preferable due to experimental fabrication cost and time. The experimental investigation of fatigue failure on stent strut following ASTM standardization. Comparing the material selection, cobalt–chromium alloy is more favorable than BMS stainless steel considering ultrathin stent strut structure for decreasing in stent restenosis effect. To design better stent structure, part of important feature are ultrathin strut, sufficient radial strength, radio-opacity and deliverability. The simulation of stent’s subcomponent illustrated the lowest safety factor by red colour contour location which was similar location on experimental testing. The fatigue failure of stent structure can be concluded mostly occur at bridge tip region or strut’s edge of stent.

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