PREPARATION OF PHYSIOLOGICALLY SIMULATED TESTING BENCHES AS PER ISO 25539 FOR THE TESTING OF VASCULAR IMPLANTS

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A thesis submitted in partial fulfillment of the requirements for the degree of
MS Biomedical Engineering and Sciences

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Acknowledgements

All praises to Almighty Allah. My parents, for their kindness and support. My supervisor Dr Murtaza Najabat Ali for his time and effort in contributing to and shaping my research; and his uncanny problem solving abilities. He has been a brilliant supervisor.

My fellow researchers and friends. These people have been a huge support for me throughout my time in NUST, and I am very thankful to them for this.

Dedication

My parents; without their encouragement and support, I would not have been able to successfully complete this research.

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Abstract:

Atherosclerosis occurs due to the accumulation of the fats, cholesterol and hardening of the calcium anywhere in the arteries. Coronary artery disease (CAD) is a type of the atherosclerosis which can cause severe heart stroke leading to the heart failure. Coronary artery stents are widely used these days as a treatment for the coronary artery disease (CAD). Stents are tubular mesh like structures of metals which are inserted by procedure known as percutaneous transluminal coronary angioplasty (PTCA). A catheter trackability testing device is required to test the trackability and resistive force encountered by catheter in the tortuous anatomy of coronary arteries in an in vitro environment. Trackability is defined as the ability of the stent and the delivery system to advance over the guide-wire along the path of vessel in a simulated anatomy. Development of this type of device is helpful in analyzing the trackability of catheters under the prevailing conditions of coronary artery which can be further used for improvement in the device design.

Chapter 1: Introduction:

Atherosclerosis is a leading cause of coronary heart disease; the root cause of atherosclerosis however, may be difficult to pin down. Its pathogenesis involves thrombotic, hemodynamic and metabolic variables along with the intrinsic structural factors related to the arterial wall. A sedentary lifestyle as well as several environmental factors may also contribute to this process [1]. The persistence of risk factors can exacerbate the likelihood of occurrence of the disease. It has been found that socioeconomic status, occupation and income might also contribute as risk factors for cardiovascular disease [2-3].

Coronary Artery disease claims 196,000 lives in Pakistan each year. It has been stipulated (World Life Expectancy-LeDuc media) that approximately 1.32 Million people will lose their lives in the next 10 years. The current solution includes the implantation of stents that are deployed in narrowed coronary arteries to keep the artery lumen open.

Coronary Artery Stents are used in a procedure called Percutaneous Coronary Intervention (PCI). Unlike coronary artery bypass surgery, stenting is considered minimally invasive because it involves no major incisions, the procedure is performed with local anesthesia or mild sedation and usually takes about an hour. Patients who undergo stenting experience significantly less discomfort and a shorter recovery time than those who undergo coronary artery bypass surgery.

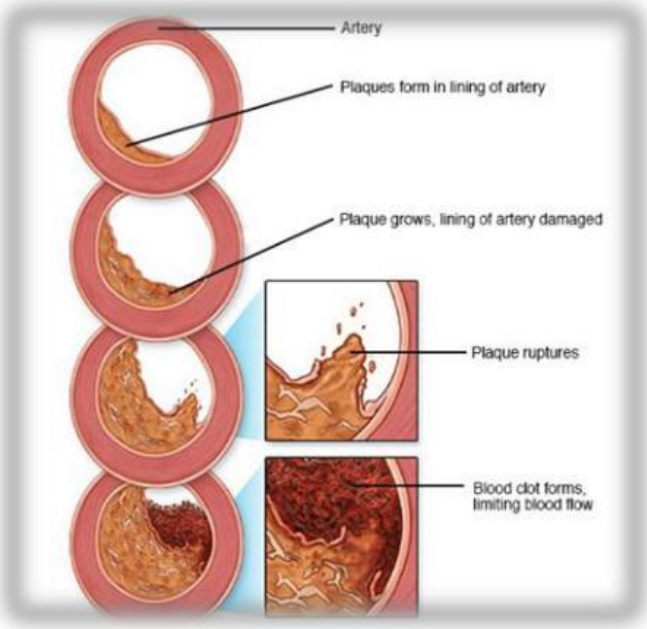

Figure 1 Progression and development of plaque and subsequent thrombosis in artery

There may be cases, when there is stent migration or build-up of plague (fatty tissue) after the stenting procedure has been completed. In such cases, secondary intervention may be required. Real-time information about in-vivo conditions of the stent and post-deployment problems is also a crucial mandate in such cases. Currently, this information is wholly dependent upon imaging/ fluoroscopy techniques. In coronary heart disease, monitoring pathological processes in real-time, could potentially revolutionize the standards of current treatment regimes. Design improvements are predicted to decrease the challenges faced currently by commercially available options [3].

To analyze the coronary stent systems and balloon catheters performance they are subjected to the series of different tests. These tests are carried out with the help of the devices made specifically for the testing these medical devices. These machines can perform tests variations of in-Vitro and ex-Vivo tests. Testing through these equipment is very expensive. It is very difficult to purchase the equipment for these tests. To fulfill the need of Medical Device Development Center an indigenously developed equipment was necessary.

In this test methods performed on the indigenously developed testing rig, the trackability of balloon catheter and stent system is determined. The testing has been carried out on test specimens that have been deployed into mock (elastically simulated) vessels.

There have been different studies which were carried out to test the trackability of balloon catheters and stent systems. Quantitative measurement of trackability testing will be a good addition for this testing which will open new ways for the designers to improve their designs of both angioplasty balloon catheters and stent systems. There is a wide use of minimally invasive stenting techniques; hence a device that can provide quantitative insight into the trackability will be of great help to both the manufacturers of coronary artery stent systems and angioplasty balloon catheters and the end-user, clinicians as well as patients who are suffering from the coronary artery disease. The key objective is to design and develop a device that can measure in vitro trackability of the delivery system. As there are many patients who suffer from coronary artery disease (CAD) every year and go through percutaneous transluminal coronary angioplasty (PTCA), this device has the potential to provide an economical yet reliable testing of the trackability of delivery systems. It is therefore expected that the general cognizance created and insights gleaned through this testing device will improve the quality of the stent systems and balloon catheters produced by the medical industry, positively impacting and revolutionizing both stent and catheter manufacturing processes and the medical device industrial bench testing regimes.

Chapter 2: Literature Review:

Angina Pectoris and Myocardial Infarction are the main complications of coronary heart diseases. The cause is mainly related to atherosclerosis, (the collection of plaque, cholesterol or fats below the endothelium layer of the coronary artery of the heart) which can lead towards the stenosis [4]. This build-up of plaque or fats inside the coronary artery causes resistance in the flow of oxygen rich blood to the walls of the heart. This disturbs the luminal patency of coronary artery and narrows artery walls that causes complications. These complications may be fatal, it has been estimated that the number of annual heart disease related deaths by the year 2030 will be about 23.3 million (5, 6).

The two major options for the treatment of coronary artery disease or coronary artery stenosis are Carotid Endarterectomy (CEA) or Coronary Artery Stenting (CAS). Much evidence has suggested that CEA may be effective in the prevention of ipsilateral ischemic events; however, this also depends on the condition of the patient. A patient with high grade stenosis may be a suitable candidate for such a procedure. However results of recent studies have suggested that CAS might be a valid alternative to CEA, since it is a less invasive procedure, requires no large incisions and does not carry the risk of cranial nerve palsy complications [14]. A systematic review covering the results of several large randomized clinical trials showed that both kinds of treatment options were ultimately associated with very similar complications. The patient age and condition needs to be considered before either treatment route is chosen [13]. FDA's Circulatory System Device Panel stated that the indication for CAS includes a patient with greater than or equal to 70% stenosis as shown by an ultrasound examination. In a study on a cost-effectiveness comparison between CAS and CEA, based on the SAPPHIRE clinical trial results, it was found that the mean post-surgery stay cost was less for stenting procedures, even though initial costs were higher. Overall, it may be concluded that the stenting provides a reasonable alternative to endarterectomy procedures [12].

Each year approximately more than one million coronary stents are implanted inside the coronary arteries [8]. A stent is a small medical device comprising of expandable mesh like tubular structure that when implanted acts as a scaffold [8] and maintains the luminal patency of stenosed artery by opening the narrow coronary artery [9]. This in turn allows the oxygenated blood to flow smoothly without any obstruction.

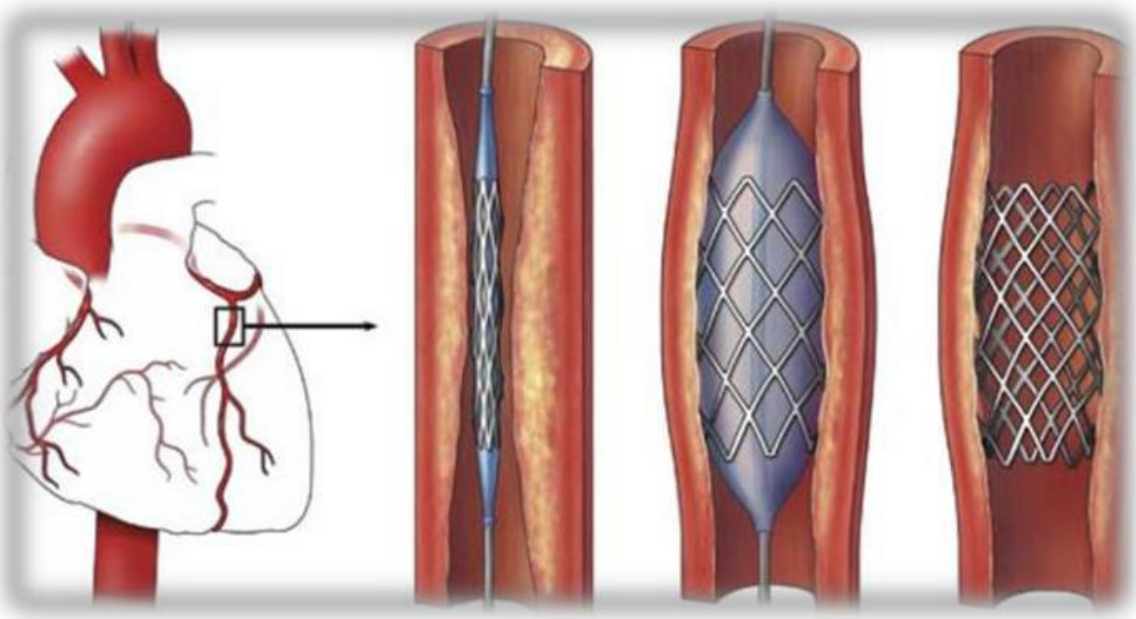

Figure 2 Stenting in coronary artery

The chances of myocardial infarction or heart attack are greatly reduced by the intervention of stents. Corrosion resistant stents (316L stainless steel, cobalt-chromium alloy and titanium) are clinically used to restore luminal patency and tissue structure inside stenosed coronary arteries [10]. In comparison to other alloys, iron based alloys have been found to have greater tensile strength [14]. It is also possible to adjust the corrosion rate of the stent by controlling the relative metallic ratios in the alloy. In one study, cobalt chromium coronary stents have been implanted in 267 patients. It was found that infrequent occurrence of adverse effects in most of the patients.

Patient monitoring was carried out through quantitative angiography techniques which revealed in-stent restenosis in 15.7% of the patients [14]. Although more and more research is being conducted in the area of polymeric stent alternatives, the thicker strut size and the lack of tensile strength are still major issues that have not been yet addressed fully.

In a clinical trial comparing polymeric scaffolds and metallic stents for maintenance of luminal patency, it was found that although the overall results are clinically comparable, there are some limitations (mainly the elongation at break of polylactides), which is why they are not dilated to the full extent during deployment.

Accordingly, there is acute gain (of the coronary lumen), after a few months [10]. In another study, polymeric stents have been subjected to uni-axial tensile tests, where it has been found that stent strut thickness and geometry matters in determining the overall radial expansion of the stents. However, geometry, strut thickness and strut angles cannot always compensate for material stiffness, which is why further research in this area is warranted and needed [7].

The imperative technique deployed to treat the stenosed artery is called PTCA (Percutaneous Transluminal Coronary Angioplasty). PTCA is an implantation technique in which a stent is deployed to dilate the stenosed artery [9]. Many metallic coronary stent designs have been developed, giving them different structural and mechanical properties [11].

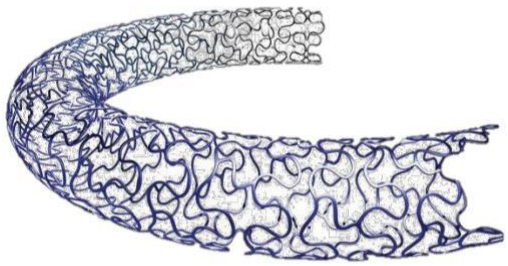

Figure 3 Bare metal stent design meant to conform to tortuous coronary arteries

Previous studies have revealed that stent design has reflective influence on neointimal proliferation [7] as well as on late lumen loss [10]. This ultimately affects post procedural intervention requirements and the rates of restenosis. Thrombogenesis and platelet activation are also considered to be affected by the design of stent [11]. However, the issues such as thrombosis, restenosis, collapses and migrations are still prevalent [12, 13].

Both commercially available categories of bare metal and drug eluting stents are available. Some examples are the ‘Cypher’, ‘Taxus’ and the ‘Endeavor’ stents. Commercially available stents have successfully addressed the issues related to arterial luminal patency and thrombosis. Commercially available stents are composed of a wire mesh design that may be expanded to maintain luminal patency of the coronary artery to restore blood flow. Bare Metal Stents may be composed of 316-L stainless steel, or Cobalt-Chromium Alloy.

Drug Eluting Stents currently available have a cytotoxic drug coating that limit neo-intimal hyperplasia, a phenomenon that may contribute to occluding arterial lumen post-stent implantation.

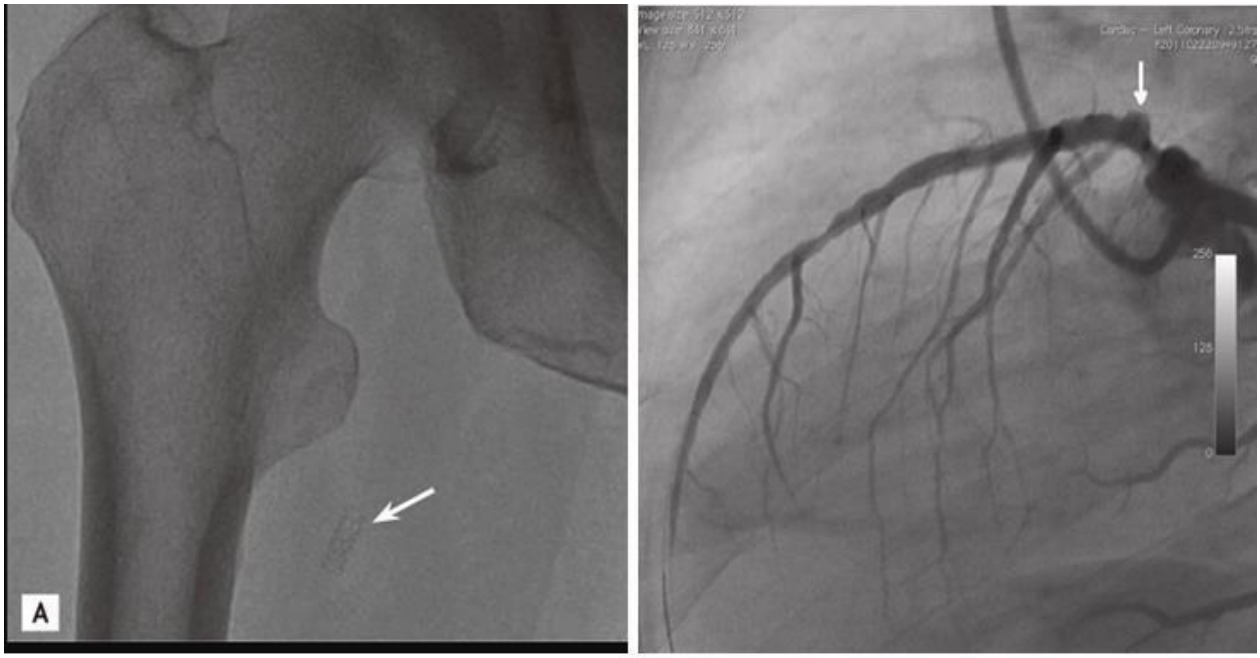

Figure 4 Angiogram with a stent that has migrated from its original point of deployment

Apart from stent thrombosis, migration may be a consequence of sub-optimal stenting. Over the years, several cases of post-implantation stent migration have been reported [17].

The major reasons listed in literature through case studies have been related to the trackability of delivery systems, which causes vascular damage and damage to the device. The clinical assessment of catheter trackability is still however, qualitative and to the best of our knowledge, the quantitative assessment of stent migration has not been reported.

Through the development and extensive in-vitro testing of an indigenously catheter trackability testing device based on design considerations listed in the standard ASTM F2394, we have attempted to quantify the resistive force encountered by catheter in the tortuous anatomy of coronary arteries in an in-vitro environment. The same study design and device may be used for different PTCA balloons with compliant, semi-compliant and

non-compliant materials. Based on our conclusions we can state that this catheter trackability testing device can be a suitable in-process quality control intervention during the mass production of coronary stent systems and angioplasty balloon catheters and may be a valuable addition to the routine inspection processes in the medical device production industry.

Chapter 3: Design and Fabrication:

3.1 Design Considerations:

3.1.1 Mock Artery:

The ASTM standard 2394-07(2017) states that the number of specimens tested for each stent geometry should be sufficient to support any claims to be made based on the test results. Three samples per test were used in this study so that the results were statistically significant. Materials that closely mimic the human coronary arterial characteristics as defined by standard ASTM F2394-07(2017)- Standard Guide for Measuring Securement of Balloon Expandable Vascular Stent Mounted on Delivery System are Latex and Silicon. Silicon tube is being used as mock artery due to the following advantages over Latex since it is more compliant, more transparent has suitable mechanical properties and has excellent re-deployability.

Figure 5 Latex and Silicon Tubes; Silcone tubes of different diameters

3.1.2 Arterial Dimensional Requirement:

According to literature review Lumen Diameter Ranges from θ1.1– θ4.6 mm [18].

	RCA dominant		Small RCA dominant		Balanced		LCA dominant	
Location	*n*	Diameter (mm)	*n*	Diameter (mm)	*n*	Diameter (mm)	*n*	Diameter (mm)
R1 middle	20	3.9±0.6	9(a)	3.8±0.5	10	3.0±0.5†	10	2.8±0.5†
R3 middle	20	3.1±0.5	10	2.6±0.6*	10	2.0±0.6†	10	1.1±0.4†
LM middle	18(b)	4.5±0.5	10	4.6±0.7	9(b)	4.4±0.4	10	4.6±0.4
L1 middle	20	3.6±0.5	10	3.8±0.4	10	3.6±0.4	10	3.7±0.2
L3 middle	20	1.7±0.5	10	1.9±0.5	10	1.8±0.4	10	2.0±0.3
C1 middle	20	3.4±0.5	10	3.5±0.8	10	3.4±0.5	10	4.2±0.6†
C3 middle	19(c)	1.6±0.6	10	2.2±0.8*	10	2.5±0.5†	10	3.2±0.5†

Table 1 Diameter ranges of lumen in coronary arteries

3.1.3 Working Fluid Requirement:

Working fluid properties should match the rheological properties of blood. As per standard guide, the following test solutions can be used:

1. Phosphate Buffer Saline (PBS)
2. Normal Saline (0.9% NaCl)
3. Distilled water
4. Any other solution compliant with isotonicity of blood

Normal Saline has been used as a working fluid in our experimental set-up.

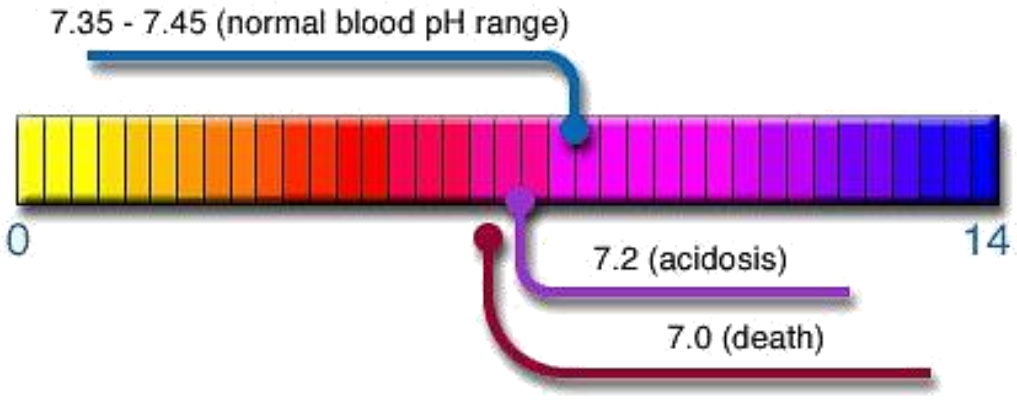

Figure 6 Ranges of acidosis and normal blood pH range

3.1.4 Temperature Requirements:

Normal body temperature can range from **97.8° F** (**36.5°C**) to **99°F** (**37.2°C**) for a healthy adult. So the temperature of the blood is slightly higher than that of the body temperature which 38 degree Celsius. Change in temperature cause change in viscosity of the fluid. As per ASTM 2394-07(2017) temperature range for the working fluid is 37± 2 C̊.

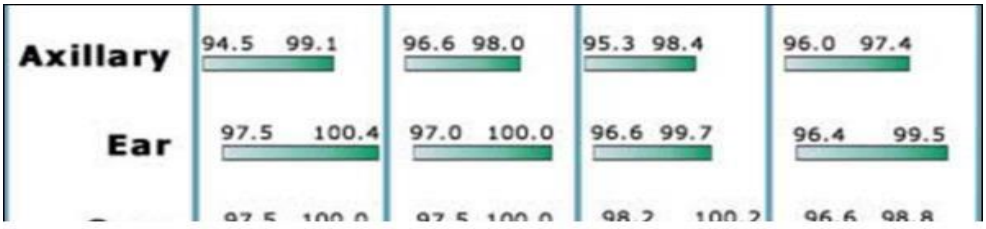

Figure 7 Ranges of body temperatures at different physiological sites

3.1.5 Force Actuation System:

For force actuation system, a linear guide actuated system was used. The catheter mounting (luer connection) was attached with the motorized linear guide system. The load cell was connected directly with the catheter mounting. A closed guide rail system was used as it has advantage over an open guide rail system. The closed guide rail system minimizes the catheter bending while being inserted into the mock artery. An

3.1.6 Load Measurement System:

For load measurement system, the following was developed. The load cell was directly attached to the catheter connector at one end and the load cell was directly mounted on to the motorized linear guide arm. Arduino based control system was connected to the load cell to get real time force values.

3.1.7 Data Acquisition System:

A catheter trackability testing program was developed for this purpose. Real time load cell data acquisition via Arduino was used. The plots acquire data on to a force time graph and the data is recorded and stored in the form of graphs.

3.2 Fabrication

3.2.1 Techniques involved

Laser Cutting along with welding was used for fabrication of guide rail and support, machining on CNC and lathe was carried out for addition of threads; drilling and manual work was carried out for the final assembly.

Figure 8 Techniques involved in the fabrication of subcomponents of the Stent Migration Testing Rig

3.3 Final Assembled Testing Set-Up

The image below shows the final trackability testing set-up with the load cell, motor, the temperature control module and the silicone mock artery assembly. All portions of the device work together as one holistic system in place to take measurements and document data.

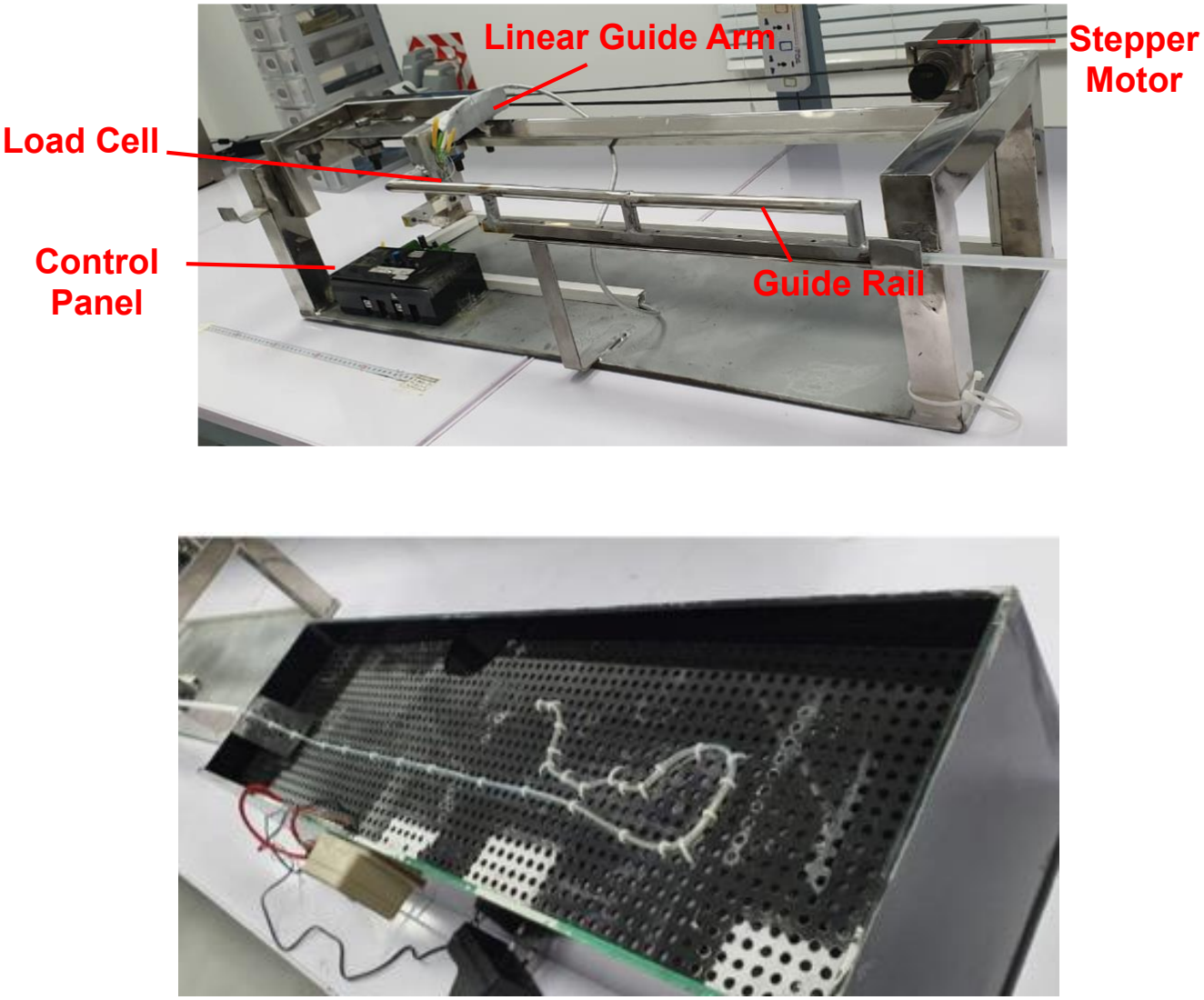

Figure 9 Assembled Trackability Testing Set-Up

3.4 Measurement and Control:

3.4.1 Temperature measurement

Temperature measurement and control was carried out through a temperature sensor (W1209) and an interface created with an Arduino UNO coupled circuit board along with a silicone tape heater.

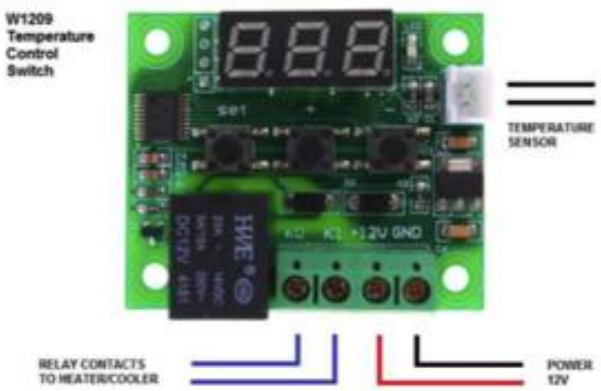

Figure 10 Temperature Control Module

The specifications of the sensor are following:

- Directly Celsius temperature calibration;
- Accuracy : 0.1 ℃
- Temperature range :-50 ℃ ~ 110 ℃
- Supply voltage : 12V
- Operating current: Less than 60μA
- Waterproof Sensor: 0.5 m

3.4.2 Temperature calibration procedure:

1. Temperature calibration was performed by calibrating the temperature sensor with an already calibrated thermocouple. Both the temperature sensor and the calibrated thermocouple were dipped in the water bath.
2. The water bath with the two temperature sensors was placed on a hot pate to gain different temperature values.
3. Readings were taken at three different temperatures by keeping the water bath at equilibrium.
4. The readings on the sensors were taken and the temperature sensor was calibrated through programming.

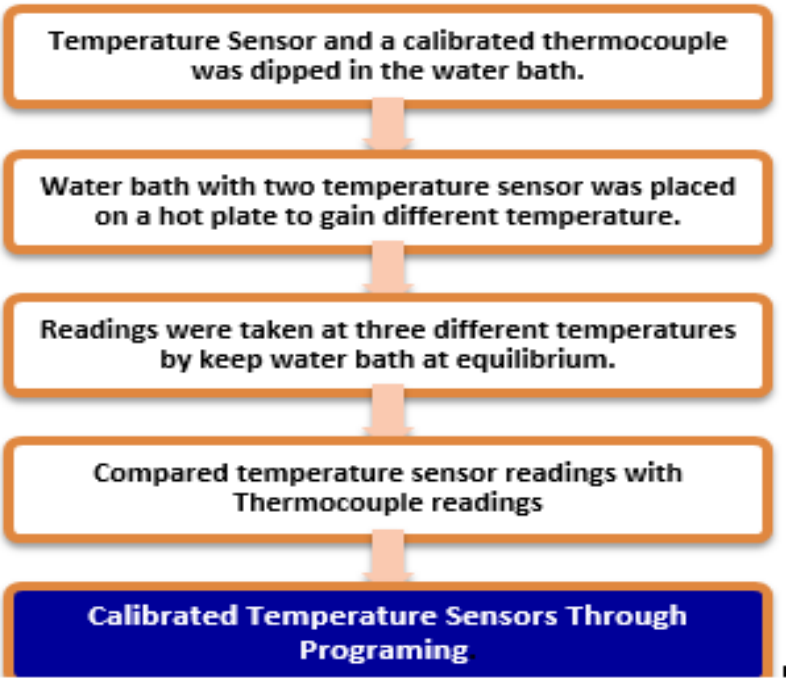

Figure 11 Temperature calibration procedure

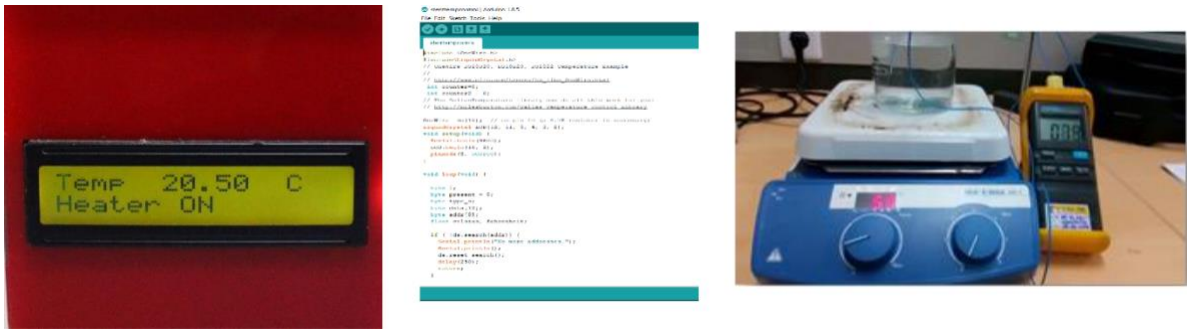

Figure 12 Temperature calibration

3.4.3 Force Measurement:

Force measurement and was carried out through a load cell and an interface created with an Arduino UNO coupled circuit board.

The specifications of the load cell are as follows:

- Capacity: 1 kg
- Rated output: 1.0 ± 0.15 mV/V
- Nonlinearity: 0.05%FS

- Repeatability: 0.03%FS
- Recommended excitation voltage: 5V
- Operating temperature range: -20 ~ +65°C

3.4.4 Force Measurement Calibration:

Calibration weights were attached to load cell. Values from weights used to calibrate load cell through programming.

3.4.5 Motor Control:

The motor along with control panel, the following specifications was used:

1. Control Panel
    - Controller = Arduino
    - Speed = 1 - 6 cm/s
    - Direction = Forward/Reverse
2. Stepper Motor Specification
    - NEMA 23 Bipolar Stepper Motor
    - Size = 56 mm x 56 mm x 76 mm
    - Weight = 1 kg
    - Current = 2.3A / coil
    - Voltage = 3.2V
    - Resistance = 1.2 Ω / coil
    - Step Angle = 1.8o (200 steps/rev)
    - Holding Torque = 19 kg-cm

Chapter 4 Measurement and Testing:

The following is the testing procedure for the testing set-up:

- Fill water bath with working fluid
- Switch on heater and temperature controller (preset at 37^{o}C)
- Allow temperature of Water Bath to stabilize
- Switch on Control Panel Module for Force Actuation & Measurement System
- Attach Balloon Catheter Luer Lock with Connector on Linear Guide Arm
- Insert Distal end of catheter into Closed Guide Rail
- Connect PC with Control Panel Module and open CTTM Program
- Press Start Button in the CTTM program to initiate real-time recording of Load Cell reading
- Press Power Button on Control Panel Module to initiate catheter motion

Catheter specification for experimentation:

Characteristics	Specification
Name	Terumo, Minitrek
Diameter	3 mm
Length	16 mm
Nominal Pressure	9 bar
Rated Burst Pressure	14 bar
Balloon material	Polyamide 12
Balloon folds	Trifolded

Chapter 5 Results and Discussion:

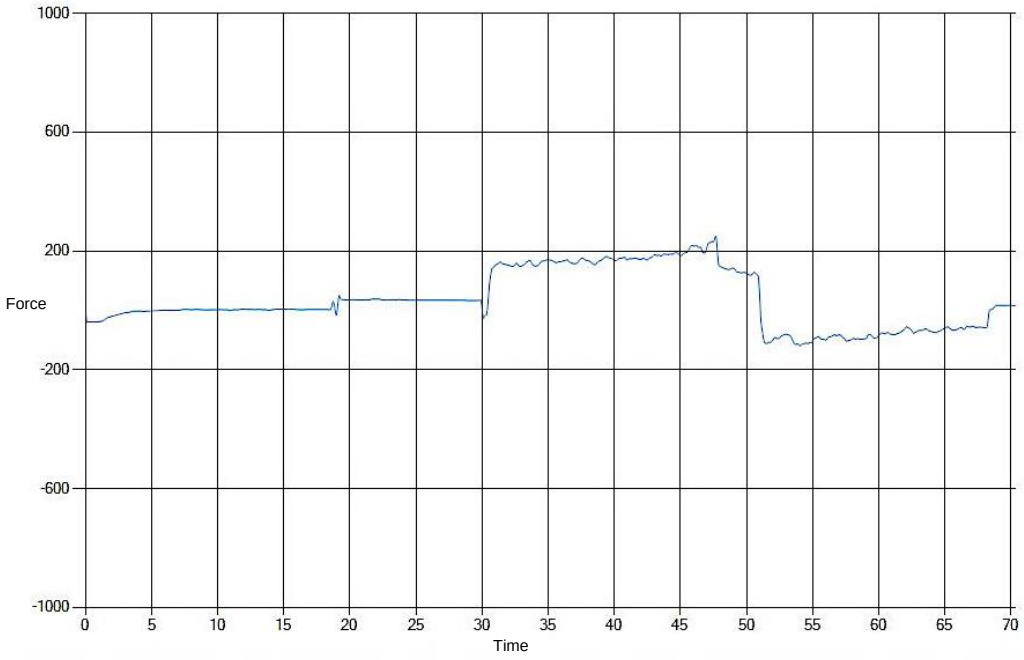

Figure 13 Test result of Abbott Minitrek balloon catheter (max. force 0.25N)

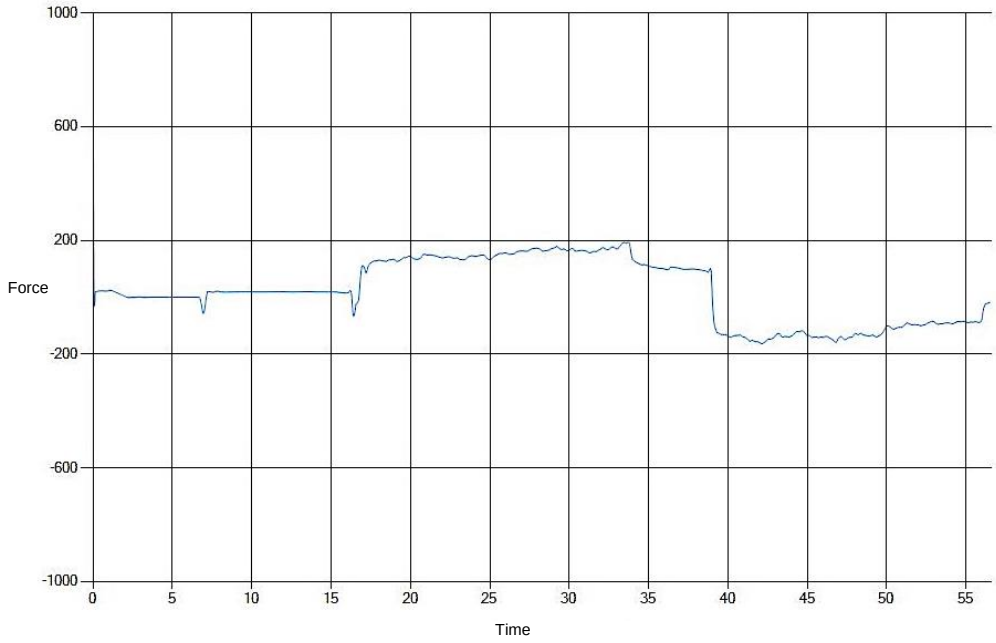

Figure 14 Test result of Terumo Ryujin balloon catheter (max. force 0.20N)

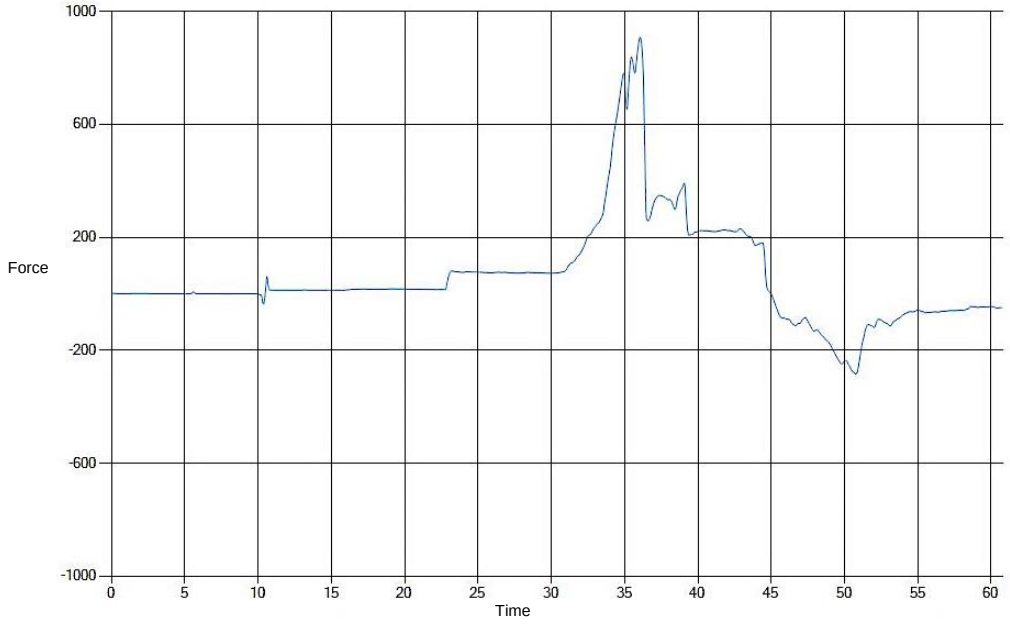

Figure 15 Test result of Sample 1 balloon catheter (max. force 0.90N)

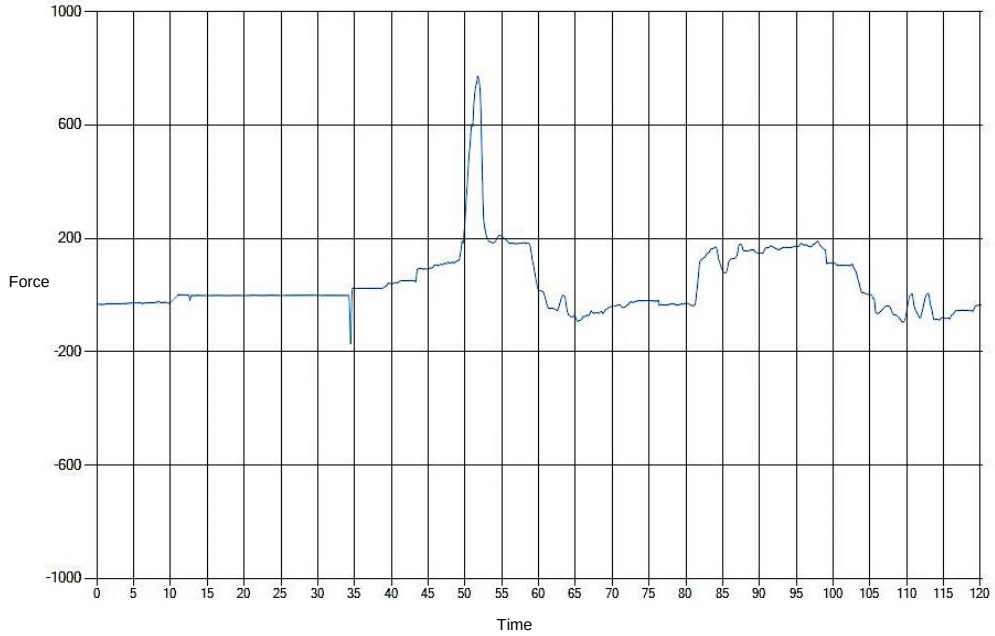

Figure 16 Test result of Sample 2 balloon catheter (max. force 0.75N

This type of bench testing may be conducted on stent systems and balloon catheters with varying geometries and lengths to determine the resistive force encountered. At high trackability forces there is a chance of increased risk of vascular damage and damage to the device; this may be ascertained effectively through bench testing on this device before clinical test phase of product development.

Chapter 6 Conclusion:

A catheter trackability testing rig was successfully designed and developed according to the specifications set out by ASTM F 2394. A few design improvements, such as the use of a camera and a binary image measurement system have also been incorporated. Our results indicate that it is possible to map out quantitative measurements of trackability forces stent systems and balloon catheters. This device has the potential to be inculcated as part of the routine bench testing and/or quality control procedures in the medical device industry. Furthermore, with regards to future research in this field, we would like to recommend certain areas that would warrant investigation, such as improved accuracy through more sensitive sensors, multiple Arterial Testing Setup, use of the high frequency motor for the improving testing speed and the inclusion of high precision camera module.

Chapter 7 References:

1. Berenson, G. S., Srinivasan, S. R., Bao, W., Newman, W. P., Tracy, R. E., & Wattigney, W. A. (1998). Association between multiple cardiovascular risk factors and atherosclerosis in children and young adults. *New England journal of medicine*, *338*(23), 1650-1656.

2. Winkleby, M. A., Jatulis, D. E., Frank, E., & Fortmann, S. P. (1992). Socioeconomic status and health: how education, income, and occupation contribute to risk factors for cardiovascular disease. *American journal of public health*, *82*(6), 816-820.

3. Fattori, R., & Piva, T. (2003). Drug-eluting stents in vascular intervention. *The Lancet*, *361*(9353), 247-249.

4. Gott, S. C., Jabola, B. A., Xu, G., & Rao, M. P. (2012, August). Vascular stents with rationally-designed surface patterning. In *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE* (pp. 1639-1642). IEEE.

5. Tan, A., Farhatnia, Y., de Mel, A., Rajadas, J., Alavijeh, M. S., & Seifalian, A. M. (2013). Inception to actualization: next generation coronary stent coatings incorporating nanotechnology. *Journal of biotechnology*, *164*(1), 151-170.

6. Cheng, A. C. (2011). Real-Time Cardiovascular Diseases Detection on a Smartphone. *Departments of Electrical and Computer Engineering, Bioengineering, Neurological Surgery and Computer Science*.

7. Hermawan, H., & Mantovani, D. (2011, November). New generation of medical implants: metallic biodegradable coronary stent. In *Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME), 2011 2nd International Conference on* (pp. 399-402). IEEE.

8. Baer, G. M., Small, W., Wilson, T. S., Benett, W. J., Matthews, D. L., Hartman, J., & Maitland, D. J. (2007). Fabrication and in vitro deployment of a laser-activated shape memory polymer vascular stent. *Biomedical engineering online*, *6*(1), 43.

9. Hermawan, H., & Mantovani, D. (2013). Process of prototyping coronary stents from biodegradable Fe–Mn alloys. *Acta biomaterialia*, *9*(10), 8585-8592.

10. Amin, F., Ali, M. N., & Minhas, M. A. (2013). An evolutionary appraisal of the efficacy of coronary artery stents relevant to the treatment of coronary heart diseases. *Int J Biomed Adv Res*, *4*, 764-775.

11. Stoeckel, D., Bonsignore, C., & Duda, S. (2002). A survey of stent designs. *Minimally Invasive Therapy & Allied Technologies*, *11*(4), 137-147.

12. Hoffmann, R., Jansen, C., König, A., Haager, P. K., Kerckhoff, G., Vom Dahl, J., ... & Mudra, H. (2001). Stent design related neointimal tissue proliferation in human coronary arteries; an intravascular ultrasound study. *European Heart Journal*, *22*(21), 2007-2014.

13. Kastrati, A., Dirschinger, J., Boekstegers, P., Elezi, S., Schühlen, H., Pache, J., ... & Schömig, A. (2000). Influence of stent design on 1-year outcome after coronary stent placement: A randomized comparison of five stent types in 1,147 unselected patients. *Catheterization and Cardiovascular Interventions*, *50*(3), 290-297.

14. Hara, H., Nakamura, M., Palmaz, J. C., & Schwartz, R. S. (2006). Role of stent design and coatings on restenosis and thrombosis. *Advanced drug delivery reviews*, *58*(3), 377-386.

15. Rosenfield, K., Schainfeld, R., Pieczek, A., Haley, L., & Isner, J. M. (1997). Restenosis of endovascular stents from stent compression. *Journal of the American College of Cardiology*, *29*(2), 328-338.

16. Wong, P., Leung, W. H., & Wong, C. M. (1996). Migration of the AVE Micro coronary stent. *Catheterization and cardiovascular diagnosis*, *38*(3), 267-273.

17. Wong, P., Leung, W. H., & Wong, C. M. (1996). Migration of the AVE Micro coronary stent. *Catheterization and cardiovascular diagnosis*, *38*(3), 267-273.

18. Dodge, J. T., Brown, B. G., Bolson, E. L., & Dodge, H. T. (1992). Lumen diameter of normal human coronary arteries. Influence of age, sex, anatomic variation, and left ventricular hypertrophy or dilation. *Circulation*, *86*(1), 232-246.

19. Onodera, K., Maruyama, Y., Tomoike, H., & Tsujioka, K. (2012). *Coronary circulation: basic mechanism and clinical relevance*. Springer Science & Business Media.