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<https://doi.org/10.5109/7323347>

出版情報 : Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 10, pp.767-772, 2024-10-17. International Exchange and Innovation Conference on Engineering & Sciences

バージョン :

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Haemodynamics in Left Ventricular Remodelling using Cardiovascular Lumped-Parameter Model

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Abstract: *Left ventricular remodelling is one of the complications of myocardial infarction. It causes the ventricle to lose contractility and to become dilate, thus changing the cardiac haemodynamics. In this study, the haemodynamic changes in left ventricular remodelling are investigated using the cardiovascular lumped-parameter model. The model simplifies blood circulation and cardiac function using electrical components such as resistor, capacitor, inductor, and diode, which represent the vessels resistance, vessels compliance, blood inertia, and heart valve, respectively. To simulate ventricular remodelling, the active and passive elastances of the left ventricle are varied by increasing and decreasing them by 10 times than the baseline values. Decreasing the active elastance reduces LV contractility, like in the case of a heart failure. Meanwhile, increasing the passive elastance makes the LV stiffer, like in the case of ventricular hypertrophy. The model eases the analysis of left ventricular remodelling without requiring complex model but will require further validation using real patients data.*

Keywords: Left ventricular remodelling; haemodynamics; lumped-parameter model, hypertrophy, ventricular dilatation

1. INTRODUCTION

Myocardial infarction (MI) or heart attack is the most common cause of a heart failure, which occurs due to myocardial ischemia [1]. Ischemia happens when the coronary artery is occluded and causes the reduction of the blood supply to the myocardium region distal to the occlusion site and causing tissue damage or sometimes, death [2]. Damaged myocardium, which usually presents in the left ventricle (LV), may lose its contractile functionality and progressively dilate, a condition known as the LV remodeling [3, 4]. LV remodeling is the changes in the shape, structure, and size of the LV as a result of physical exercise, injury to the cardiac muscle, and cardiac diseases such as MI [5]. It is the major determinant of the long-term outcomes following MI and has been associated with heart failure and cardiovascular death at long-term follow-up [1].

LV remodeling could be assessed through medical imaging modalities such as computed tomography (CT) scan and Magnetic resonance imaging (MRI) [6]. However, assessing post-ischemic myocardium using medical imaging modalities requires multiple time scanning and high cost [6]. To overcome the limitations of medical imaging modalities, finite element (FE) models of the heart have been widely used as a prediction tool for disease progression, especially MI [2, 4, 7-10].

Nevertheless, the use of FE models to predict the effect of LV remodeling is time consuming and requires high computational resources as it usually only can be seen after a long period of time. Thus, a lumped-parameter model is developed to overcome the limitations of FE models. In this model, the haemodynamics behavior of the blood in blood vessel and heart are modelled using electrical elements such as the resistors, capacitors and inductors, that represent the blood vessel resistance, compliance, and inertial effect, respectively [11].

Several studies have simulated the cardiovascular circulation using lumped parameter model [11-13]. However, these studies did not completely model the whole heart and circulation during myocardial infarction and ventricular remodeling. Therefore, this study aims to investigate the haemodynamics in the left ventricle undergoing remodelling using the cardiovascular lumped-parameter model. The model is built upon the work by [11, 13], which consists of the systemic and pulmonary blood circulation and the whole heart mechanics. The haemodynamics parameters to be investigated are the cardiac chambers volume and pressure, particularly LV, left atrium (LA), and right ventricle (RV).

2. METHODOLOGY

2.1 Cardiovascular lumped-parameter model

The cardiovascular lumped-parameter model used in this study consists of a set of ordinary differential equations relating the volume, V and pressure, P of the cardiac chambers and the volumetric blood flow, Q out from and into the heart chambers. The system of equations is as follows:

$$\frac{dV_{LA}}{dt} = Q_{p,ven} - Q_{mitral} \quad (1)$$

$$\frac{dV_{LV}}{dt} = Q_{mitral} - Q_{aortic} \quad (2)$$

$$\frac{dV_{RA}}{dt} = Q_{s,ven} - Q_{tricuspid} \quad (3)$$

$$\frac{dV_{RV}}{dt} = Q_{tricuspid} - Q_{pulmonary} \quad (4)$$

$$\frac{dP_{s,art}}{dt} = \frac{1}{C_{s,art}} (Q_{aortic} - Q_{s,art}) \quad (5)$$

$$\frac{dP_{s,ven}}{dt} = \frac{1}{C_{s,ven}} (Q_{s,art} - Q_{s,ven}) \quad (6)$$

$$\frac{dP_{p,art}}{dt} = \frac{1}{C_{p,art}} (Q_{pulmonary} - Q_{p,art}) \quad (7)$$

$$\frac{dP_{p,ven}}{dt} = \frac{1}{C_{p,ven}} (Q_{p,art} - Q_{p,ven}) \quad (8)$$

$$\frac{dQ_{s,art}}{dt} = \frac{1}{L_{s,art}} (P_{s,art} - P_{s,ven} - Q_{s,art}R_{s,art}) \quad (9)$$

$$\frac{dQ_{s,ven}}{dt} = \frac{1}{L_{s,ven}} (P_{s,ven} - P_{RA} - Q_{s,ven}R_{s,ven}) \quad (10)$$

$$\frac{dQ_{p,art}}{dt} = \frac{1}{L_{p,art}} (P_{p,art} - P_{p,ven} - Q_{p,art}R_{p,art}) \quad (11)$$

$$\frac{dQ_{p,ven}}{dt} = \frac{1}{L_{p,ven}} (P_{p,ven} - P_{LA} - Q_{p,ven}R_{p,ven}) \quad (12)$$

Here, the meaning of each subscript is as follows: *LA* – left atrium; *LV* – left ventricular; *RA* – right atrium; *RV* – right ventricular; *s,art* – systemic arterial; *s,ven* – systemic venous; *p,art* – pulmonary arterial; *p,ven* – pulmonary venous.

Furthermore, the blood vessels resistance, compliance, and inertial are represented by the terms *R*, *C*, and *L*, respectively. The values of these parameters are presented in Table 1. Figure 1 shows the circuit arrangement equivalent to the cardiovascular lumped-parameter model.

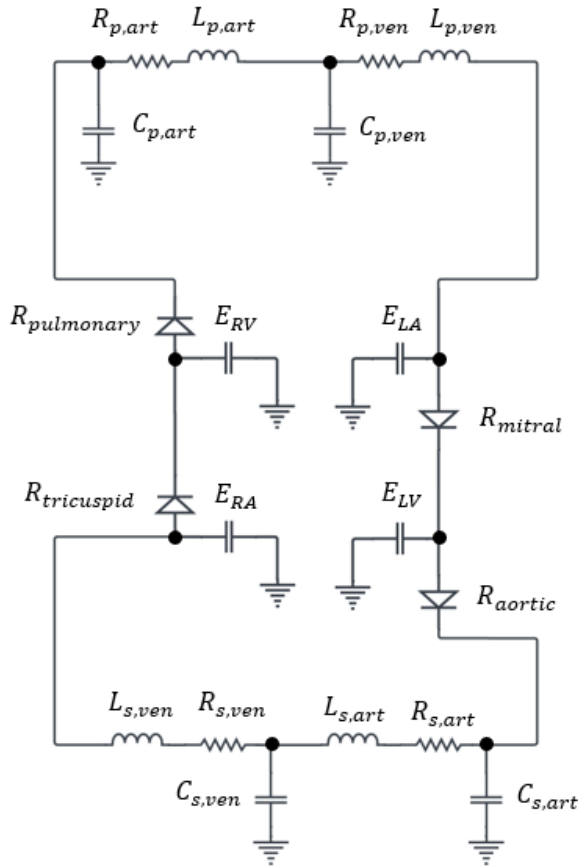


Fig. 1. Cardiovascular lumped-parameter model circuitry arrangement.

The mechanical properties of each of the heart chamber is defined using the time-varying elastance *E*, which is then related to the chamber pressure, as follows:

$$P_{LV} = P_{ext} + E_{LV}(V_{LV} - V_{LV_0}) \quad (13)$$

$$P_{LA} = P_{ext} + E_{LA}(V_{LA} - V_{LA_0}) \quad (14)$$

$$P_{RV} = P_{ext} + E_{RV}(V_{RV} - V_{RV_0}) \quad (15)$$

$$P_{RA} = P_{ext} + E_{RA}(V_{RA} - V_{RA_0}) \quad (16)$$

where P_{ext} is the external pressure exerted on the heart and V_0 represents the initial heart chamber volume.

Meanwhile, the time-varying elastance *E* is given as:

$$E = E_a e(t) + E_b \quad (17)$$

where E_a and E_b are the active and passive elastances, respectively, and $e(t)$ is a function for the heart chamber contraction, as has been used in [11, 13], defined as:

$$e(t) = \begin{cases} \frac{1}{2} \left(1 - \cos \left(\frac{\pi}{T_C} (t - t_c) \right) \right), & 0 \leq t - t_c < T_C \\ \frac{1}{2} \left(1 + \cos \left(\frac{\pi}{T_R} (t - t_R) \right) \right), & 0 \leq t - t_R < T_R \\ 0, & \text{otherwise} \end{cases} \quad (18)$$

Here, T_C and T_R refer to the period of the heart chamber contraction and relaxation, while t_c and t_R refer to the time when the contraction and relaxation start. The values of the time constants are given in Table 2.

Then, the flow into and out from the heart passing the valves are modelled using the diodes as follows:

$$Q_{mitral} = \frac{1}{R_{mitral}} (P_{LA} - P_{LV}) \quad (19)$$

$$Q_{aortic} = \frac{1}{R_{aortic}} (P_{LV} - P_{s,art}) \quad (20)$$

$$Q_{tricuspid} = \frac{1}{R_{tricuspid}} (P_{RA} - P_{RV}) \quad (21)$$

$$Q_{pulmonary} = \frac{1}{R_{pulmonary}} (P_{RV} - P_{p,ven}) \quad (22)$$

The valve resistance, R_v is determined using the following if-else rules:

$$R_v = \begin{cases} R_{open}, & P_i \geq P_o \\ R_{close}, & P_i < P_o \end{cases} \quad (23)$$

where P_i and P_o represent the first and second pressure terms in equations (19) to (22).

2.2 Model parameters for LV remodelling

The model baseline parameters are presented in Table 1, as obtained by [13]. During LV remodelling, it was found that the LV elastance may increase or decrease up to 7% from its original value [12]. Therefore, to simulate LV remodelling, the LV elastances, both active E_a and passive E_b , are varied by decreasing and increasing its value by 10 times from the baseline, as shown in Table 3. In this study, a one-at-a-time (OAT) sensitivity analysis is performed, where either the value of E_a or E_b of the LV elastance is varied while maintaining the other at the original value.

Throughout this article, the following units are used for all parameters and variables: time – s; resistance – mmHg.s/mL; compliance – mL/mmHg; elastance – mmHg/mL; pressure – mmHg; flow – mL/s; and volume – mL.

Table 1. Model parameters

Model parameter	Value	Model Parameter	Value
$R_{s,ven}$	0.3200	V_{RV_0}	16.000
$R_{p,ven}$	0.0357	V_{RA_0}	4.0000
$C_{s,ven}$	60.000	R_{open}	0.0075
$C_{p,ven}$	10.000	R_{close}	75000
$L_{s,art}$	0.0050	$E_{a,LA}$	0.0700
$L_{s,ven}$	0.0005	$E_{b,LA}$	0.1800
$L_{p,art}$	0.0005	$E_{a,RA}$	0.0600
$L_{p,ven}$	0.0005	$E_{b,RA}$	0.0700
V_{LV_0}	42.000	$E_{a,RV}$	0.5500
V_{LA_0}	4.0000	$E_{b,RV}$	0.0500

Table 2. Time constants for the elastance function

Time constant	LA	LV	RA	RV
T_C	0.17	0.25	0.17	0.25
T_R	0.17	0.4	0.17	0.4
t_c	0.9	0.1	0.9	0.1

Table 3. Variation of LV elastance

LV elastance	Baseline	Case 1	Case 2	Case 3	Case 4
E_a	3.35	0.335	33.5	3.35	3.35
E_b	0.2	0.2	0.2	0.02	2.0

2.3 Numerical and Analysis Procedure

The lumped-parameter model is solved using a standard ODE15s solver in MATLAB. The model is simulated for 8 cardiac cycles with a time step of 1 ms. For all the simulations, automated time-stepping is used. Figure 2 shows the LV pressure-volume curve for the model using baseline parameters values. The curves have the same pattern for all 8 cardiac cycles under baseline parameters values.

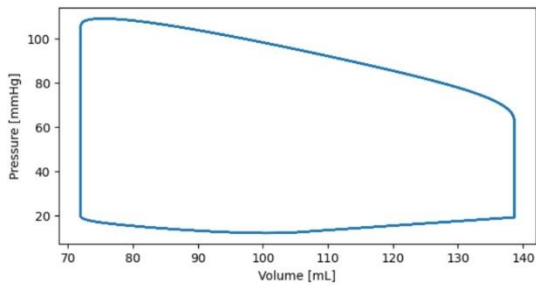


Fig 2: LV pressure-volume curves for the model using baseline parameters.

Two haemodynamics parameters will be investigated, namely the pressure and volume, for three cardiac chambers, namely the LV, RV, and LA. The haemodynamic changes in RA were not investigated here because it was found that the changes in RA pressure and volume were not significant (results not shown).

Furthermore, the left ventricular ejection fraction (LVEF) is also used to determine the amount of blood pumped out from LV over time. It is determined using the following equation:

$$LVEF = \frac{SV}{EDV} \quad (24)$$

where SV and EDV are the stroke volume and end-diastolic volume, respectively. SV can be calculated using the following relationship:

$$SV = V_{LV,max} - V_{LV,min} \quad (24)$$

where $V_{LV,max}$ and $V_{LV,min}$ are maximum and minimum LV volume, respectively. For a normal healthy heart, LVEF is around 50% to 75% [14].

3. RESULTS

3.1 Pressure changes in heart chambers

Figure 3(a) shows the pressure-time curves for LV for all the cases. The normal LV pressure obtained is in between 10 to 100 mmHg, which is within the range of an actual heart pressure of 10 to 130 mmHg [15]. For case 1 and 2,

the LV maximum pressure drops to 50 mmHg and increases to 140 mmHg, respectively. This shows that the effects are more significant when reducing E_a by 10 times from the baseline. The LV pressure drops significantly when reducing E_a shows a similar finding in a heart failure due to LV remodelling [16], where the LV starts to lose its ability to pump blood out.

For case 3, decreasing E_b by 10 times from the baseline causes the LV pressure to increase, but gradually decreases over time and reaches the baseline pressure. However, for case 4, when E_b is increased by 10 times from the baseline, the LV pressure drops significantly and does not regain its baseline value as the cycle increases. This finding shows that the LV pressure is affected more by increasing E_b . Higher E_b means that the LV becomes harder to be filled with blood. Thus, the end diastolic volume is reduced and hence, reduce the pressure needed to pump the blood out [17]. This is similar in LV remodelling cases [16], where the heart becomes stiffer.

The other chambers are also affected by the LV remodelling, as shown in Figure 3(b) and 3(c). However, increasing E_a does not significantly affect the LA and RV pressures. Significant effects of LV remodelling on the LA and RV pressures can only be observed for cases 1, 3, and 4.

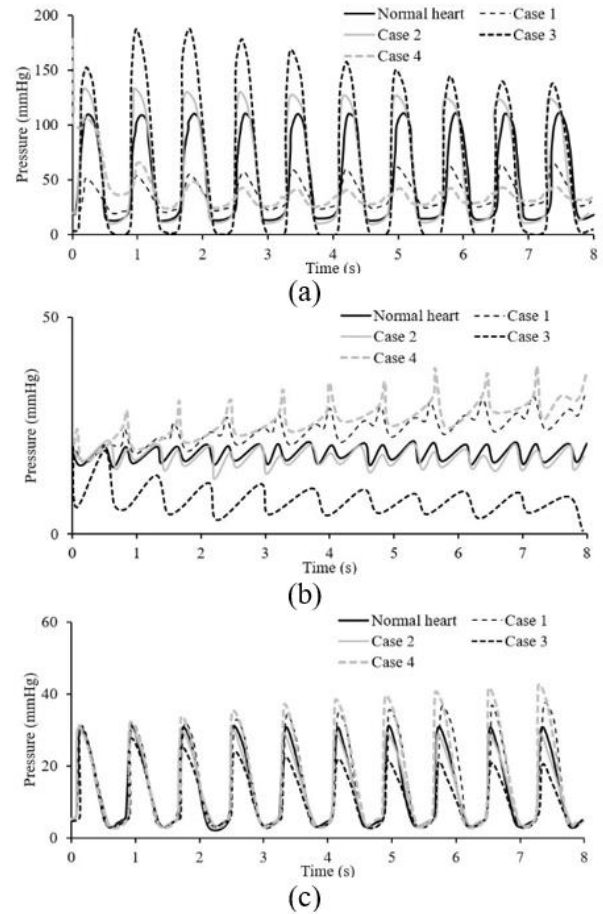


Fig 3: Pressure-time curves for (a) LV, (b) LA, and (c) RV.

3.2 Volume changes in heart chambers

Figure 4 shows the variations of LV, LA, and RV volume with time. The LA and RV volumes do not change

significantly for case 2 only. To further understand the variations of the chamber volume during LV remodelling, LVEF is calculated. From this simulation, the normal heart has LVEF of about 68%. This will be used as the baseline for the comparison for other cases.

For case 1, the LVEF obtained is about 48% and below the LVEF of a normal heart. This shows that the LV is not able to pump adequate amount of blood when E_a drops by 10 times from the baseline. LV remodelling has been shown to cause a reduction in LVEF [18].

For case 2, the LVEF is 80% when E_a is 10 times than the baseline. This is in contrast from case 1. This shows that the amount of blood pumped out of LV is more than needed. This phenomenon of increasing LVEF after increment of E_a is particularly observed in the stroke volume of athletes, where the LVEF is high probably due to the occurrence of LV remodelling after continuous physical activities [19].

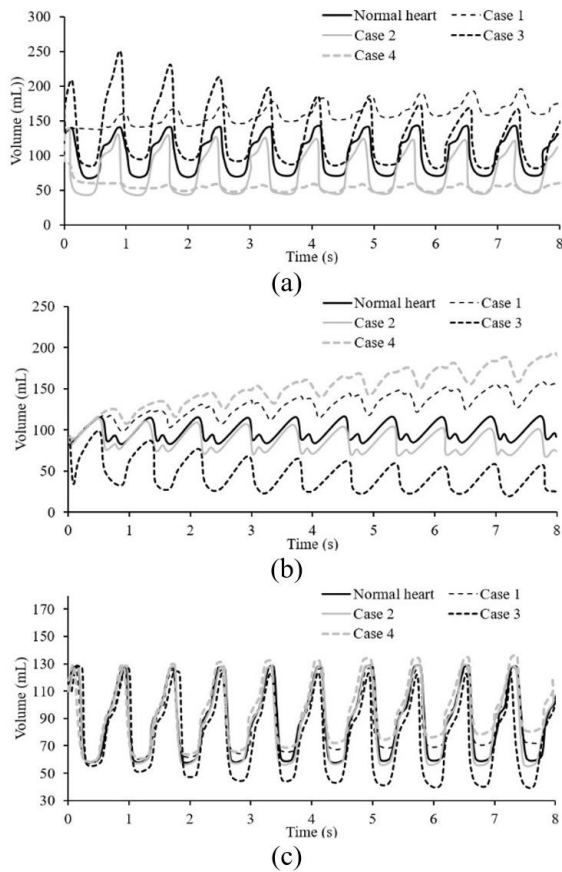


Fig. 4: Volume-time curves for (a) LV, (b) LA, and (c) RV.

For case 3, the LVEF drops to 38% only. In this case, drops in E_b causes LV to have higher end diastolic volume, but at the same time the LV pressure maintains the same. Hence, the LV is unable to pump the excess blood out [16].

Lastly, for case 4, the LV volume maintains roughly at about 50 mL throughout the cardiac cycle. This is due to the LV pressure drops significantly from the baseline. This shows that when E_b is increased by 10 times from the baseline, the LV becomes stiff, similar to the case of ventricular hypertrophy. In ventricular hypertrophy, the LV is thickened and its pumping efficiency drops [20].

4. DISCUSSION

LV remodelling can occur due to physical exercise such as happening in athletes [5], and cardiac diseases such as MI [4], hypertrophy [20], and cardiomyopathy [10]. This causes changes in the size, shape, and structure of the LV. Simulating the changes using 3-dimensional model is difficult because it requires high computational cost due to the model complexity [2, 4]. The cardiac lumped-parameter presented here allows for a simplified analysis of LV remodelling because it is in 1-dimensional, yet it can mimic the behaviour of a normal heart, as presented in Figure 3(a) and 4(a).

In this study, LV remodelling is simulated using the cardiac lumped-parameter model by varying the LV elastance. LV elastance is divided into two parts, namely the active elastance, E_a and passive elastance, E_b . An OAT sensitivity analysis was performed, whereby one elastance is varied while fixing the other. Four cases were presented: (1) E_a decreased by 10 times from baseline; (2) E_a increased by 10 times from baseline; (3) E_b decreased by 10 times from baseline; and (4) E_b increased by 10 times from baseline. The justification of doing this analysis is that during LV remodelling, the elastance is either increased or decreased, and the cardiac contractility is also changed, which is in this case is represented by the changing the E_a . The work done by [12] evaluated the effect of MI by adding the elastance for infarct in the myocardium. Meanwhile, the work by [21] studied LV remodelling by adding stress and strain based stimuli into the LV cavity and wall volume in a 1-dimensional lumped-parameter model. Our method is simple as it only requires modification of the elastance values.

For case 1, reducing the E_a by 10 times from the baseline causes a significant reduction in LV pressure. In heart failure, LV contractility reduced as a result of LV remodelling [16]. Reducing the E_a also resulted in the reduction in LVEF, which shows that the LV loses its ability to pump blood out to the other parts of the body. This is also observed in the case of LV remodelling, in which it causes a reduction in LVEF [18]. Meanwhile, for case 2, increasing the E_a by 10 times from the baseline does not give significant effect on the LV pressure. It also resulted in an increased of LVEF. Increasing E_a produces haemodynamics findings similar to an athlete [19], in which the heart contractility increases to accommodate for increasing requirements of blood supply to the other muscles.

For case 3, E_b is decreased by 10 times from the baseline. The LV pressure initially increases but gradually decreases and reaches the baseline pressure. It also produces 38% of LVEF. A low passive elastance means that the ventricle is less stiff and has higher end diastolic volume. Despite having higher end diastolic volume, its contractility remains the same as baseline, and thus, the LV is unable to pump the blood adequately. This case might be similar to the case of ventricular dilatation [22], a condition when the LV becomes enlarge causes its wall to becomes thinner and reduces its pumping ability. However, our findings suggest that the LV becomes dilate due to the reduction in E_a , while the contractility remains the same. This also causes the LV to not be able

to remove the blood out even though it can contain more blood volume.

For case 4, increasing E_b 10 times from the baseline resulted in the LV becomes stiffer, similar to the case of ventricular hypertrophy [20]. In this case, the LV volume remains about the same throughout the cardiac cycle, indicating that the LV experiencing very small contraction. In ventricular hypertrophy, the ventricle becomes thickened and its ability to contract reduces [20].

The lumped-parameter model has the potential to be used to mimic cases of LV remodelling. It also has been used to study the effect of aging on LV remodelling [11]. However, several limitations have been identified. The study only modifies the LV elastance to simulate LV remodelling. In fact, LV remodelling may also result in the changes in the elastance of other chambers, such as the RV [23]. Furthermore, LV remodelling may affect both active and passive elastance at the same time. Our study utilized OAT sensitivity analysis, but it provides insights on the effect of varying each of the elastance.

Investigating LV remodelling using the coupling of lumped-parameter model with FE model of the heart could provide more insights. For example, the work by [13] utilized a biventricular FE model coupled with a lumped-parameter model. The biventricular model by [24, 25] includes the model of cardiac Purkinje fibre for a more extensive analysis of cardiac haemodynamics. Many cardiac diseases, such as MI, also affect the myocyte electrophysiology. Various cardiac electrophysiological models have been developed to investigate the effects of MI [8, 9, 26, 27]. Combining these models with biventricular model and the lumped-parameter model, could further elucidate haemodynamics effects during LV remodelling.

The lumped-parameter model can also be used to study the overall haemodynamics effects of blood vessels diseases by coupling it with 3-dimensional blood vessels models, for examples [28-30]. This could also be extended to investigate the effects of LV remodelling towards haemodynamics in the blood vessels, such as the aorta and coronary artery.

5. CONCLUSION

A cardiac lumped-parameter model has been used to investigate the effects of LV remodelling on the heart haemodynamics. The pressure and volume of the heart chambers, namely LV, LA, and RV were investigated. LV remodelling was simulated by varying both the active and passive LV elastance. Decreasing the active elastance reduces LV contractility, like in the case of a heart failure. Meanwhile, increasing the passive elastance makes the LV stiffer, like in the case of ventricular hypertrophy. The model could be used, alongside 3-dimensional FE model, to investigate various effects of LV remodelling.

6. ACKNOWLEDGEMENT

This research is funded by Malaysia Ministry of Higher Education under the Fundamental Research Grant Scheme (Grant ID: FRGS/1/2022/TK0/UMP/02/41 &

RDU220129) and Tabung Persidangan Luar Negara (TPLN).

7. REFERENCES

- [1] Kobayashi, K., Maeda, K., et al. (2017). Dynamics of angiogenesis in ischemic areas of the infarcted heart. *Sci Rep*, 7(1), 7156. doi:10.1038/s41598-017-07524-x
- [2] Wan Ab Naim, W. N., Mohamed Mokhtarudin, M. J., et al. (2021, 1-3 March 2021). *The Effect of Variation of Myocardium Wall Thickness on the Evolution of Ischemic Heart Wall Stress and Movement: A Computational Modelling Study*. Paper presented at the 2020 IEEE-EMBS Conference on Biomedical Engineering and Sciences (IECBES). doi:10.1109/IECBES48179.2021.9398744
- [3] Dorsey, S. M., McGarvey, J. R., et al. (2015). MRI evaluation of injectable hyaluronic acid-based hydrogel therapy to limit ventricular remodeling after myocardial infarction. *Biomaterials*, 69, 65-75. doi:10.1016/j.biomaterials.2015.08.011
- [4] Mohamed Mokhtarudin, M. J., Shabudin, A., et al. (2018, 3-6 Dec. 2018). *Computational Model of Left Ventricle Infarct Remodelling during Passive Filling Phase*. Paper presented at the 2018 IEEE-EMBS Conference on Biomedical Engineering and Sciences (IECBES). doi:10.1109/IECBES.2018.8626651
- [5] Muhl, C., Dassen, W. R. M., et al. (2008). Cardiac remodelling: concentric versus eccentric hypertrophy in strength and endurance athletes. *Netherlands Heart Journal*, 16(4), 129-133. doi:10.1007/BF03086131
- [6] Ibanez, B., Aletras, A. H., et al. (2019). Cardiac MRI Endpoints in Myocardial Infarction Experimental and Clinical Trials: JACC Scientific Expert Panel. *J Am Coll Cardiol*, 74(2), 238-256. doi:10.1016/j.jacc.2019.05.024
- [7] Chan, B. T., Ahmad Bakir, A., et al. (2019). Impact of myocardial infarction on intraventricular vortex and flow energetics assessed using computational simulations. *International Journal for Numerical Methods in Biomedical Engineering*, 35(6), e3204. doi:10.1002/cnm.3204
- [8] Wan Ab Naim, W. N., Mokhtarudin, M. J. M., et al. (2020). The study of border zone formation in ischemic heart using electro-chemical coupled computational model. *International Journal for Numerical Methods in Biomedical Engineering*, 36(11), e3398. doi:10.1002/cnm.3398
- [9] Wan Ab Naim, W. N., Mohamed Mokhtarudin, M. J., et al. (2021). The study of myocardial ischemia-reperfusion treatment through computational modelling. *Journal of Theoretical Biology*, 509, 110527. doi:10.1016/j.jtbi.2020.110527
- [10] Marwan, S. H., & Todo, M. (2019). *Biomechanical analysis of hypertrophic cardiomyopathy behavior of human heart using dynamic finite element method*. Paper presented at the Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES), Kyushu. doi:10.15017/2552937
- [11] Muhammad Ali, S. M., El-Bouri, W., et al. (2022, 7-9 Dec. 2022). *Age-Based Sensitivity Analysis on*

- Cardiac Hemodynamics using Lumped-Parameter Modelling*. Paper presented at the 2022 IEEE-EMBS Conference on Biomedical Engineering and Sciences (IECBES). doi:10.1109/IECBES54088.2022.10079315
- [12] Pilla, J. J., Gorman, J. H., 3rd, et al. (2009). Theoretic impact of infarct compliance on left ventricular function. *Ann Thorac Surg*, 87(3), 803-810. doi:10.1016/j.athoracsur.2008.11.044
- [13] Regazzoni, F., Salvador, M., et al. (2022). A cardiac electromechanical model coupled with a lumped-parameter model for closed-loop blood circulation. *Journal of Computational Physics*, 457, 111083. doi:10.1016/j.jcp.2022.111083
- [14] Kosaraju, A., Goyal, A., et al. (2017). *Left Ventricular Ejection Fraction*: StatPearls Publishing, Treasure Island (FL).
- [15] Oh, G. C., & Cho, H.-J. (2020). Blood pressure and heart failure. *Clinical Hypertension*, 26(1), 1. doi:10.1186/s40885-019-0132-x
- [16] Tsai, C.-H., Pan, C.-T., et al. (2021). Left ventricular remodeling and dysfunction in primary aldosteronism. *Journal of Human Hypertension*, 35(2), 131-147. doi:10.1038/s41371-020-00426-y
- [17] Zhong, L., Ghista, D. N., et al. (2005). Passive and active ventricular elastances of the left ventricle. *BioMedical Engineering OnLine*, 4(1), 10. doi:10.1186/1475-925X-4-10
- [18] Galli, A., & Lombardi, F. (2016). Postinfarct Left Ventricular Remodelling: A Prevailing Cause of Heart Failure. *Cardiology Research and Practice*, 2016(1), 2579832. doi:10.1155/2016/2579832
- [19] Vella, C. A., & Robergs, R. A. (2005). A review of the stroke volume response to upright exercise in healthy subjects. *British Journal of Sports Medicine*, 39(4), 190. doi:10.1136/bjism.2004.013037
- [20] Giamouzis, G., Dimos, A., et al. (2022). Left ventricular hypertrophy and sudden cardiac death. *Heart Failure Reviews*, 27(2), 711-724. doi:10.1007/s10741-021-10134-5
- [21] Rondanina, E., & Bovendeerd, P. H. M. (2020). Evaluation of stimulus-effect relations in left ventricular growth using a simple multiscale model. *Biomechanics and Modeling in Mechanobiology*, 19(1), 263-273. doi:10.1007/s10237-019-01209-2
- [22] Little, W. C. (2005). Diastolic Dysfunction Beyond Distensibility. *Circulation*, 112(19), 2888-2890. doi:10.1161/CIRCULATIONAHA.105.578161
- [23] Haddad, F., Hunt, S. A., et al. (2008). Right Ventricular Function in Cardiovascular Disease, Part I. *Circulation*, 117(11), 1436-1448. doi:10.1161/CIRCULATIONAHA.107.653576
- [24] Ahmad Bakir, A., Al Abed, A., et al. (2018). A Multiphysics Biventricular Cardiac Model: Simulations With a Left-Ventricular Assist Device. 9. doi:10.3389/fphys.2018.01259
- [25] Ahmad Azahari, A. F. A., Wan Ab Naim, W. N., et al. Advancement in computational simulation and validation of congenital heart disease: a review. *Computer Methods in Biomechanics and Biomedical Engineering*, 1-14. doi:10.1080/10255842.2024.2377338
- [26] Wan Ab Naim, W. N., Mohamed Mokhtarudin, M. J., et al. (2021, 1-3 March 2021). *Study of Oxygen Deprivation on Cardiomyocyte using Electro-chemical Coupled Mathematical Model*. Paper presented at the 2020 IEEE-EMBS Conference on Biomedical Engineering and Sciences (IECBES). doi:10.1109/IECBES48179.2021.9398825
- [27] Mohd Nor, P. N. A. N., & Mohamed Mokhtarudin, M. J. (2022). *Modelling the effect of ischemia on myocardial electrophysiology*. Paper presented at the Engineering Technology International Conference (ETIC 2022), Malaysia. doi:10.1049/icp.2022.2671
- [28] Dey, S., Ibtida, T., et al. (2020). *Difference between non-Newtonian Carreau and Casson blood viscosity models to predict hemodynamics in idealized eccentric arterial stenosis: large eddy simulation modeling*. Paper presented at the Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES), Kyushu. doi:10.5109/4102499
- [29] Che Amdilah, N. S., Lau, Y. S., et al. (2022, 7-8 Sept. 2022). *Computational fluid dynamics of patient-specific coronary artery during stent treatment*. Paper presented at the Engineering Technology International Conference (ETIC 2022), Malaysia. doi:10.1049/icp.2022.2608
- [30] Tan, W. T., Liew, Y. M., et al. (2021). Effect of Vessel Tortuosity on Stress Concentration at the Distal Stent-Vessel Interface: Possible Link With New Entry Formation Through Biomechanical Simulation. *Journal of Biomechanical Engineering*, 143(8). doi:10.1115/1.4050642