ELECTRODE PLACEMENT BASED ON MULTIOBJECTIVE OPTIMIZATION FOR ELECTROCARDIOGRAPHY T-SHIRT

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Say, “Work. God will see your work, and so will His Messenger, and the believers. Then you will be returned to the Knower of secrets and declarations, and He will inform you of what you used to do.”

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ABSTRACT

Although electrocardiography (ECG) t-shirts have some advantages, obtaining the signal-to-noise ratio (SNR) of the captured ECG signal as high as traditional ECGs remains challenging. Reducing the number of electrodes by employing limited-lead systems has been an approach to minimize artifacts. However, the accuracy and correlation of the derived 12-lead ECG remain a problem. Electrode placement for ECG t-shirts should consider two aspects to maximize the SNR including the electrophysiological and practical aspects. These aspects should be quantified for computing purposes. Unfortunately, the existing studies have not quantified the practical aspects. Additionally, the previous research formulated them in a single objective function for optimization, whereas both aspects are independent. This study is aimed to maximize the SNR of ECG t-shirts using limited-lead systems by trading-off between the two aspects. It has three objectives: to improve accuracy and correlation of the synthesized 12-lead ECG by segmenting the ECG waveform, to quantify some factors in electrode placement (including ECG signal amplitude, skin-shirt gap, relative shirt movement, and regional sweat rate) for optimization purposes, and to improve SNR by compromising electrophysiological and practical aspects in the electrode placement. In this study, one cycle of ECG is divided into three segments: P, QRS, and ST. Each segment is transformed to obtain a derived 12-lead ECG signal. This proposed segment-specific (SS) approach is then compared to conventional full-cycle (FC) by using six existing methods: Dower's method with generic coefficients, Dower's method with individual (patient-specific) coefficients, linear regression (LR), 2nd-degree polynomial regression (PR), 3rd-degree PR, and artificial neural network (ANN). Simulations using 3DS Max® and MATLAB® were carried out to quantify the ECG signal amplitude, skin-shirt gap, relative shirt movement, and regional sweat rate into variables in the range of [0,1], called *satisfaction degrees*. These variables represent the likelihood of the placement of electrodes. Multi-objective optimization (MOO) is employed to find the optimal electrode placement, i.e., high SNR, by compromising electrophysiological and practical aspects. As a result, the new SS approach outperformed the conventional method (FC). It has significantly reduced the transformation error up to 30.94% and improved the transformation correlation as high as 4.89%. The simulations have successfully quantified the electrophysiological and practical aspects of electrode placement into satisfaction degrees. The MOO yielded Pareto optimal solutions to assist decision-makers in selecting the final solution subjectively. Based on the experiment results, this new approach improved the SNR as high as 29.44%. This study provides a comprehensive method for determining the location of the electrodes to support ECG t-shirt manufacturers.

ABSTRAK

Walaupun *t-shirt* elektrokardiografi (EKG) mempunyai beberapa kelebihan, namun usaha untuk mendapat isyarat yang mempunyai kualiti isyarat-ke-bunyi (*signal-to-noise-ratio*/SNR) setinggi EKG tradisional kekal mencabar. Mengurangkan bilangan elektrod dengan menggunakan sistem sadap terhad (*limited lead*) telah menjadi suatu pendekatan untuk meminimumkan artifak. Walau bagaimanapun, ketepatan dan korelasi EKG 12-sadap yang diperoleh kekal sebagai suatu masalah. Peletakan elektrod untuk *t-shirt* EKG seharusnya mempertimbangkan dua aspek iaitu untuk memaksimumkan SNR melalui aspek-aspek elektrofisiologi dan praktikal. Aspek-aspek ini harus dihitung untuk tujuan pengkomputeran. Malangnya, kajian-kajian semasa tidak mempertimbangkan aspek-aspek praktikal dalam kajian mereka. Tambahan pula, penyelidikan terdahulu merumuskannya dalam satu fungsi objektif untuk pengoptimuman, sedangkan kedua-dua aspek ini tidak saling bergantung. Kajian ini bertujuan untuk memaksimumkan SNR *t-shirt* EKG yang menggunakan sistem sadap terhad dengan mengkompromikan kedua-dua aspek. Kajian ini mempunyai tiga objektif, iaitu meningkatkan ketepatan dan korelasi isyarat EKG 12-sadap yang disintesis dengan membahagikan bentuk gelombang EKG, untuk mengukur beberapa faktor dalam penempatan elektrod (termasuk amplitud isyarat EKG, jarak *t-shirt* dan kulit, pergerakan relatif baju dan kadar peluh) untuk tujuan pengoptimuman, dan untuk meningkatkan SNR dengan mengkompromikan aspek-aspek elektrofisiologi dan praktikal dalam peletakan elektrod. Dalam kajian ini, satu kitaran EKG dibahagikan kepada tiga segmen: P, QRS, dan ST. Setiap segmen diubah untuk memperoleh isyarat EKG 12-sadap. Pendekatan segmen khusus (*segment-specific*/SS) yang dicadangkan ini kemudian dibandingkan dengan pendekatan konvensional (*full-cycle*/FC) dengan menggunakan enam kaedah yang ada: kaedah Dower dengan pekali generik, kaedah Dower dengan pekali individu (khusus pesakit), regresi linear, regresi polinomial darjah ke-2, regresi polinomial darjah ke-3, dan rangkaian saraf tiruan. Simulasi menggunakan 3DS Max® dan MATLAB® dilakukan untuk mengukur amplitud isyarat EKG, jarak *t-shirt* dan kulit, pergerakan relatif baju dan kadar peluh menjadi pemboleh ubah dalam kisaran [0,1], yang disebut *tahap kepuasan*. Pemboleh ubah ini mewakili kemungkinan peletakan elektrod. Pengoptimuman multiobjektif (*Multiobjective optimization*/MOO) digunakan untuk mencari penempatan elektrod yang optimum, iaitu SNR tinggi, dengan mengkompromikan aspek-aspek elektrofisiologi dan praktikal. Kajian ini menunjukkan, pendekatan SS baru yang diukur di dalam kajian ini telah mengatasi kaedah konvensional (FC). Pendekatan SS juga telah mengurangkan ralat transformasi dengan ketara sehingga 30.94% dan meningkatkan korelasi transformasi setinggi 4.89%. Simulasi berjaya menghitung aspek-aspek elektrofisiologi dan praktikal peletakan elektrod menjadi *tahap kepuasan*. MOO pula berjaya menghasilkan penyelesaian optimum Pareto untuk membantu para pembuat keputusan dalam memilih penyelesaian akhir secara subjektif. Berdasarkan keputusan eksperimen, pendekatan baru ini dapat meningkatkan SNR setinggi 29.44%. Kajian ini telah berjaya mengetengahkan kaedah yang komprehensif untuk menentukan lokasi elektrod untuk membantu pengeluar *t-shirt* EKG.

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LIST OF ABBREVIATIONS

3D	-	Three Dimensional
ANN	-	Artificial Neural Network
ANT	-	Adaptive Network Topology
ARVD	-	Arrhythmogenic Right Ventricular Dysplasia
BLE	-	Bluetooth Low Energy
BPM	-	Beats Per Minute
BSPM	-	Body Surface Potential Mapping
CAD	-	Coronary Artery Disease
CMRR	-	Common-Mode Rejection Ratio
CNN	-	Convolutional Neural Network
CVD	-	Cardiovascular Disease
DAQ	-	Data Acquisition
DC	-	Direct Current
DM	-	Decision Maker
EASI	-	*(not an abbreviation)*
ECG	-	Electrocardiography
EEG	-	Electroencephalography
EMG	-	Electromyography
EMI	-	Electromagnetic Interference
EU	-	European Union
FC	-	Full Cycle
IEC	-	International Electrotechnical Commission
IoT	-	Internet of Things
LR	-	Linear Regression
LSTM	-	Long Short-Term Memory Network
MECG	-	Multichannel Electrocardiography
MOO	-	Multiobjective Optimization
MSE	-	Mean Square Error
OT-PVC	-	Outflow Tract Premature Ventricular Contraction
PDMS	-	Polydimethylsiloxane

PEDOT	-	Polyethylenedioxythiophene
P-FCB		Planar Fashionable Circuit Board
PR	-	Polynomial Regression
PVDF	-	Polyvinylidene fluoride or polyvinylidene difluoride
RLD	-	Righ-Leg Drive
RMSE	-	Root Mean Square Error
RSR	-	Regional Sweat Rate
SNR	-	Signal-to-Noise Ratio
SS	-	Segment Specific
SVR	-	Support Vector Regression
TOPSIS	-	Technique for Order of Preference by Similarity to Ideal Solution
USA	-	United States of America
WHO	-	World Health Organization

LIST OF SYMBOLS

μ	-	Friction Coefficient
F	-	Force
V	-	Voltage
Z	-	Impedance
I	-	Electrical Current
β	-	Transformation Coefficient
r	-	Correlation Coefficient
u	-	Satisfaction Degree
ω	-	Angular Frequency
$S(\omega)$	-	Power Spectral Density

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

1.1.1 Wearable ECG

Cardiovascular diseases (CVD), including coronary heart disease, heart failure, hypertension, and stroke, have caused more than 17 million deaths and remain the world's highest cause of death (WHO, 2018; Benjamin *et al.*, 2017). A number of studies have been carried out in order to reduce the number of deaths. An effective approach to reducing this number is through preventative lifestyles and early diagnosis (Zheng *et al.*, 2014; Habetha, 2006; Shomaji *et al.*, 2019; Cuba Gyllensten *et al.*, 2016; Dzau and Balatbat, 2017); for instance, personalized cardiovascular disease monitoring devices (Vemishetty *et al.*, 2016). One of the techniques is incorporating an ECG into wearable devices, called wearable ECG. For long-term monitoring, wearable ECGs are preferred for practical reasons (Rashkovska *et al.*, 2020).

Wearable devices have been implemented in sport, medical, fashion, personal protective equipment, and military applications (Ismar *et al.*, 2020). Many are incorporated with the internet of things (IoT) (Jiang, 2020; Trobec *et al.*, 2018). Communication security, energy efficiency, and wearable computing are the most concern currently (Seneviratne *et al.*, 2017).

Wearable electronics were first introduced in the 1990s. Afterwards, a number of wearable electronics have been introduced, such as wearable ECG, wearable health systems, smart textiles, smart clothing, smart wear, interactive textiles, smart fabrics, sensate liners, e-broidery, functional & intelligent clothing, communication textiles, wearable intelligence, wearable sensors, and textile motherboards (Tröster, 2011; Yoo, 2013; Mukhopadhyay, 2015; Fiedler *et al.*, 2012; Lou *et al.*, 2020).

A human-centered approach to design wearable sensors has been proposed by researchers (Totter, Bonaldi and Majoe, 2011). They proposed a 2-dimensional matrix to design wearable sensors by considering two aspects: instrumental qualities and user experience. This matrix can be a good guideline for garment industries to design wearable ECGs. A framework aiming to bring smart clothing research to the market has been designed by researchers (Park and Jayaraman, 2010). They proposed the roadmap in three steps: establishing robustness and finalizing the system, demonstrating clinical effectiveness, and holistic cost-benefits analysis. Establishing robustness can be performed by identifying sensors for long-term use, eliminating motion artifacts, improving signal processing and communication module, simplifying the user interface, developing technologies for mass production, and testing the integrated system.

According to EU medical device regulation, a wearable ECG for long-term monitoring can be categorized as a class IIa (Rashkovska *et al.*, 2020); hence, a notified body approval is required. A bio-amplifier should have input impedance larger than 3 GΩ frequency to meet the IEC60601 requirements of signal distortion (Maji and Burke, 2020).

Table 1.1 summarizes the existing wearable ECG technologies (Chi, Jung and Cauwenberghs, 2010; Ozkan *et al.*, 2020). Some wearable ECG products offer some additional features, such as replaceable electrodes, battery alert, low power, and emergency request. Several products provide smartphone apps, webpage, data storage, medical history, and geographical location. ANT, Bluetooth low energy (BLE), Bluetooth, and Zigbee technologies are employed for wireless communication to connect the device to the network infrastructure. Power consumption is the primary consideration.

Table 1.1 Wearable ECG technologies summary

Electrodes	Wet, textile, polymer composite, metal plate, dry-noncontact (capacitive)
Circuit	Passive, active
Electrodes location	T-shirt, on-phone, chair, belt, on-body, vest, bra, singlet
The textile electrodes can be replaced?	Yes, no
Battery alert?	Yes, no
Battery life	1~14 days
Memory	No memory, local, server, local & server
Medical history	Yes, no
Smartphone apps	Yes, no
Webpage	Yes, no
Data transferring	ANT, BLE, cable, Bluetooth, Zigbee
Geographical location	Yes, no
Emergency request	Yes, no

Some products utilize conventional wet electrodes. Other devices have used dry electrodes, such as textile, polymer, composite, and metal plate. The others use non-contact electrodes, which work using the capacitive principle. The electrode can be passive or active (i.e., equipped with a preamplification module close to the electrode). Active electrodes are employed to obtain a good signal-to-noise ratio (SNR). On the other hand, passive electrodes are widely used due to their simplicity and low cost.

There are several types of wearable ECGs in the market, such as T-shirts, on-phone, chairs, belts, on-body, vests, bra, and singlets. One of the T-shirt advantages is that the manufacturer can place the electrodes in any position on the body to obtain the best SNR, unlike the other types. Usually, the ECG T-shirts utilize passive textile electrodes. In this thesis, the term *ECG T-shirt* is used to describe a T-shirt containing integrated ECG electrodes.

1.1.2 Dry Electrodes and SNR

Several studies have proposed T-shirt designs for heart monitoring using various types of electrodes (Cho *et al.*, 2011; Hoffmann and Ruff, 2007; Gruetzmann, Hansen and Müller, 2007; Zelle, Fiedler and Haueisen, 2012; Cheng *et al.*, 2008; Fuhrhop, Lamparth and Heuer, 2009; Acar *et al.*, 2019; Lee and Cho, 2019). The material of the electrodes is required to be suitable for long-term applications.

For long-term monitoring, dry electrodes are more preferred than conventional wet/gelled electrodes. Its gel-free characteristic can reduce adverse effects on the skin, e.g., irritation (Hoffmann and Ruff, 2007). Due to these reasons, dry electrodes have been employed widely. Unfortunately, some problems that decrease the SNR remain with the use of dry electrodes; for example, motion artifacts and baseline drift caused by respiration and muscle activity (Takeshita *et al.*, 2019; Xiong and Chen, 2019; Cho, Lim and Cho, 2016; Tsukada *et al.*, 2019). Reducing motion artifacts to obtain a high SNR has been a significant challenge in the ECG smart garment design (Xiong *et al.*, 2019). Hence, non-contact electrodes (e.g., capacitive sensors), which have high sensitivity to motion artifacts, are less common (Chi, Jung and Cauwenberghs, 2010). Various hardware designs and signal processing techniques have been implemented to reduce motion artifacts in order to improve the SNR. This thesis aims to obtain a high SNR for the ECG T-shirt.

1.1.3 Limited-Lead Systems

Another concern in wearable ECGs is the number of electrodes. The number of electrodes in wearable ECG should be less to minimize artifacts. Reducing the number of electrodes resulted in less sensitivity to artifacts during moving the body (Kaewfoongrungsi and Hormdee, 2018). The standard 12-lead ECG with ten electrodes has been established as a gold standard in medical applications. Limb, augmented, and precordial leads were introduced by Einthoven (in 1908), Goldberger (in 1942), and Wilson (in 1944), respectively (Malmivuo and Plonsey, 1995). However, it needs ten electrodes; hence, impractical for long-term monitoring (24-hour), wearable ECG, and ambulatory applications. Its high number of electrodes affects sensitivity to wiring noise & motion artifacts as well as difficulties in attaching electrodes (Kaewfoongrungsi and Hormdee, 2018). Furthermore, non-clinical users are not well-trained to locate the electrodes properly, while misplacing the electrodes causes misdiagnosis (Kania *et al.*, 2014).

Several systems which employ fewer electrodes, called "derived 12-lead ECG systems" (or "limited-lead systems"), have been investigated to overcome this gap. The goal is to capture the ECG signal using a limited number of electrodes (i.e., less than ten as in the 12-lead system) without significantly reducing the amount and reliability of the acquired information.

Various studies in the limited-lead systems have been carried out since 1968, aiming to reduce the number of electrodes (Tomasic and Trobec, 2014). Several lead systems with a limited number of electrodes have been introduced, e.g., the EASI lead system (Philips-Medical-Systems, 2007; Dower *et al.*, 1988), which employs five electrodes only. *Eigenleads*, which employ three bipolar leads, were introduced to reconstruct the standard 12-lead ECG identified from the extrema of the resulting eigenvectors (Finlay *et al.*, 2010). Another approach utilized three differential leads to synthesize a 12-lead ECG (Trobec and Tomašić, 2011). EASI has been widely implemented due to its simplicity (Jahrsdoerfer, Giuliano and Stephens, 2005).

The basic principle of the limited-lead system is synthesizing a 12-lead ECG (i.e., I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, and V6) from ECG signals captured by the limited-lead system using a transformation matrix. Coefficients of the transformation matrix need to be optimized to maximize the accuracy (minimize the error) and maximize the correlation of the derived signals. Optimizing the transformation coefficients is one of the objectives of this thesis.

1.1.4 Electrode Placement

Electrode placement is critical for ECGs. Electrode misplacement may result in an incorrect diagnosis. Misplacing electrodes has been a problem for years. This kind of technical errors may cause misinterpretation of the ECG signal. A prepositioned-electrode system has been introduced by researchers to overcome this problem (Roy *et al.*, 2020).

Electrodes should be placed on locations that capture the highest signal amplitude and lowest artifacts to obtain maximum SNR. Some researchers connected sensing technologies (including wearable ECG sensors) with chemistry, material science, and engineering research. They concluded that electrode placement causes constraints on electrode materials and system designs (Ray *et al.*, 2019).

A survey of electrode placement has been presented by some researchers (Soroudi *et al.*, 2019). Unfortunately, those electrode placement methods were based on the consideration of electrophysiological aspects only (i.e., the ECG signal amplitude or correlation with the standard 12-lead) without considering the practical aspects. Due to their dynamic environment, both electrophysiological and practical aspects need to be considered for ECG T-shirt application (Finlay *et al.*, 2008; Cheng *et al.*, 2013; Soroudi *et al.*, 2019; Cho and Lee, 2015). This thesis uses the term *practical* to describe aspects in electrode placement other than electrophysiology.

Several studies introduced qualitative consideration of practical scenarios for electrode placement (Finlay *et al.*, 2008). However, quantifying the practical aspects is necessary for mathematical calculation. After quantified, both electrophysiological and practical aspects need to be included to optimize the electrode placement. Since both are independent of each other, a compromise (trade-off) of both aspects is proposed in this thesis.

1.1.5 Personalized ECG

The most effective electrode placement is different for each person and each ECG feature, i.e., disease-specific and patient-specific (Tröster, 2011). ECG signal distribution varies among individuals. Personalized treatment may result in better diagnosis and, in turn, will reduce the healthcare cost. A project about personalized and integrated cardiac care using patient-specific cardiovascular modeling (named EuHeart) has been performed (Smith *et al.*, 2011; Krueger *et al.*, 2013) by involving 16 partner organizations from six countries. Besides the mentioned advantages, the personalized design of the ECG T-shirt also may increase the level of comfort for the users as the size is appropriate for them instead of the general sizing system. The electrode placement method in this thesis is limited to personalized T-shirts.

1.2 Problem Statement

Obtaining the best SNR in ECG T-shirts remains challenging. Limited-lead systems, which employ fewer electrodes than the standard 12-lead system, are recommended for ECG T-shirts to minimize artifacts. Electrophysiological and practical aspects need to be considered for electrode placement.

For ECG T-shirts, the number of electrodes should be less to minimize noise caused by artifacts, which decreases the SNR. Some studies have derived the standard 12-lead ECG from limited-lead systems. However, the accuracy and correlation of the derived 12-lead ECG still need to be improved. This thesis hypothesizes that accuracy and correlation can be improved by segmenting the ECG waveform instead of calculating a full-cycle ECG like the existing studies. The EASI lead system, which is one of the limited-lead systems, was utilized in this thesis to evaluate the hypothesis as it has been widely used in medical applications.

To maximize SNR, electrode placement for ECG T-shirts should consider two aspects: electrophysiological and practical. Practical aspects should be concerned due to its dynamic environment. These two aspects need to be quantified into normalized numbers in the range of [0,1] for computing purposes, e.g., optimization. Quantifying the electrophysiological can be performed by measuring the ECG signal amplitude. Unfortunately, the existing studies have not quantified the practical aspects. Besides quantifying the electrophysiological, this thesis proposes quantifying the practical aspects, including the skin-shirt gap, relative shirt movement, and regional sweat rate (RSR).

Electrophysiological and practical aspects need to be optimized to obtain electrode placement with a high SNR. Since both aspects are independent of each other, a compromise (trade-off) is proposed in this thesis instead of formulating them in a single objective function as presented by the existing studies. Each aspect is represented in an objective function; hence there will be two objective functions. This thesis proposes an optimization method to place electrodes by compromising these two objective functions.

1.3 Aim and Objectives of the Study

The major aim of this study is to maximize the SNR of ECG T-shirts using limited-lead systems. This study has three objectives:

1) To improve accuracy and correlation of the synthesized 12-lead ECG, which is derived from the EASI lead system, by segmenting the ECG waveform;

2) To quantify some factors in electrode placement, including ECG signal amplitude, skin-shirt gap, relative shirt movement, and RSR, into normalized numbers in the range of [0,1] for optimization purposes;

3) To improve SNR by compromising electrophysiological and practical aspects in electrode placement.

1.4 Significance of the Study

Wearable healthcare devices (particularly personalized medical devices), including ECG T-shirts, are emerging technologies with a continuously growing market. Therefore, research in this field has significant impacts.

This study proposes some techniques that may help manufacturers to place electrodes in an ECG T-shirt. Firstly, this thesis proposes a new approach to improve the transformation accuracy and correlation of the derived 12-lead ECG. By this approach, the 12-lead ECG can be synthesized by a limited-lead system. After that, a method is proposed to quantify some factors affecting the electrode placement (ECG signal amplitude, skin-shirt gap, relative shirt movement, and RSR) into normalized numbers in the range of [0,1]. It is beneficial for computation/optimization purposes.

Lastly, a new method is proposed to improve SNR by compromising electrophysiological and practical aspects of electrode placement instead of formulating them in a single objective function. This study may provide a comprehensive method for determining the location of the electrodes to help ECG T-shirt manufacturers.

1.5 Scope of the Study

The scope of the study is described as follows:

- This study aims to maximize the SNR of ECG T-shirts from a personalized-design point of view, instead of a generic approach which requires many experiment subjects for the statistical hypothesis. However, this personalized approach has advantages, as mentioned earlier in Problem Background.

- This study focuses on the optimization method. Some simulation data and optimization parameters were taken from other published papers as the experiments were too complex and out of the focus of this study. The validity of some of the optimization parameters can be more deeply investigated in separate studies, which are not in the scope of this thesis.
- This study used the male model and subject; however, the proposed method can be applied to females. The human model was assumed as a solid collision object in the simulation; some of its physical properties were not covered.
- This study focuses on electrode placement. The electrode dimension, which influences the placement, was not considered in this thesis.
- The EASI lead system was utilized in this study to evaluate the hypothesis; however, the proposed method can be applied to other limited-lead systems.

1.6 Thesis Outline

This thesis is arranged into six chapters. Chapter 1 starts with the background of the study, including wearable ECG, dry electrodes, SNR, limited-lead systems, electrode placement, and personalized ECG. Some research gaps are discussed. Hypothesis and proposed solutions are then formulated in Problem Statement. The aims and objectives of this study are determined based on the hypothesis and the proposed solutions. The significance of the study is presented in this chapter to describe the research impacts. This chapter also explains the scope of the research and the thesis outline.

Chapter 2 discusses state-of-the-arts related to this study. It covers dry-contact electrodes, electrode connection, limited-lead systems, electrode placement, electrophysiological & practical aspects of electrode placement, and relationships among factors affecting electrode placement. Some research gaps are mentioned in this literature review.

Chapter 3 explains the methodology of this study through a flowchart. This chapter also explains the detail of simulations and experiments to achieve the study's objectives, which cover placement using the standard lead system, practical and electrophysiological aspects, and compromise between practical and electrophysiological aspects.

Chapter 4 presents simulation and experimental results conducted in Chapter 3. Data are presented in tables and graphs, followed by some discussions. Some data are attached in Appendixes. This chapter concludes with a chapter summary to ensure the research objectives are achieved.

Chapter 5 discusses the results from Chapter 4 in more detail. Some related works are also mentioned in the discussion. This chapter also discusses the limitations of the study for future investigations.

Finally, Chapter 6 concludes and summarizes the works in this study. The contribution of the research to the existing knowledge is also presented in this chapter as well as recommendations for future work.

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2) Mulyadi, I.H., Nelmiawati and Supriyanto, E. (2019). Improving accuracy of derived 12-lead electrocardiography by waveform segmentation. *Indonesian Journal of Electrical Engineering and Informatics*. 7(1), 15–21. doi: 10.11591/ijeei.v7i1.937. **(Scopus Indexed)**
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