J. Health Inform. *2022 Janeiro-Março; 14(1): 3-10* **Original Article**

JHI JOURNAL OF HEALTH INFORMATICS

Wearable technology for electrocardiogram and vectocardiogram using the Dower Transformation

Tecnologia vestível para exames de eletrocardiograma e vetocardiograma utilizando a transformada de Dower

Tecnología vestible para exámenes de electrocardiograma y vetocardiograma utilizando de la transformada de Dower

Vinícius Rodrigues Zanon[1], Eliel Marcos Rocha Romancini [2], Fabrício de Oliveira Ourique[3], Analúcia Schiaffino Morales[3]

Keywords: Wearable Device; Electrocardiogram; Vectorcardiogram

ABSTRACT

Objectives: Thousands of people suffer from cardiovascular diseases. Even though the electrocardiogram is an exam consolidated. The lack of methodological observation in the placement of sensors can compromise the results. This article proposes a wearable vest capable of conditioning cardiac signals from three simultaneous channels, reducing the chance of failures in the exam due to the smaller number of electrodes attached to the patient's body. **Methods:** It adds the vectorcardiogram technique to the electrocardiogram wearable, which consists of three orthonormal derivations Vx, Vy, and Vz, measuring dynamic components of the heart vector. **Results:** The display of the cardiac biopotential in the web-mobile application represents the visualization of the twelve derivations synthesized from the Dower transform and the spatial projections of the cardiac loop under a three-dimensional view. **Conclusion:** Feasibility of integrating the vectorcardiogram with the electrocardiogram exam.

Descritores: Dispositivo Vestível; Eletrocardiograma; Vetocardiograma

RESUMO

Objetivos: Milhares de pessoas sofrem com doenças cardiovasculares, apesar do Eletrocardiograma ser um exame consolidado, a falta de observação metodológica na colocação dos sensores pode comprometer os resultados. O presente artigo propõe um colete vestível capaz de condicionar sinais cardíacos de três canais simultâneos, reduzindo a chance de falhas na execução do exame em função da menor quantidade de eletrodos fixados ao corpo do paciente. **Métodos**: Acrescenta a técnica do vetocardiograma ao vestível de eletrocardiograma, que consiste em três derivações ortonormais Vx, Vy e Vz, medindo componentes dinâmicos do vetor coração. **Resultados**: Exibição do biopotencial cardíaco na aplicação web-mobile representa de forma satisfatória a visualização das doze derivações sintetizadas a partir da transformada de Dower, bem como, as projeções espaciais do loop cardíaco sob uma visão tridimensional. **Conclusão**: Viabilidade de integração do vetocardiograma ao exame de eletrocardiograma.

Descriptores: Tecnología Vestible; Electrocardiograma; Vetocardiograma

RESUMEN

Objetivos: Miles de personas padecen enfermedades cardiovasculares, a pesar de que el electrocardiograma es un examen consolidado, la falta de observación metodológica en la colocación de sensores puede comprometer los resultados. Este artículo propone una tecnología vestible capaz de acondicionar las señales cardíacas de tres canales simultáneos, reduciendo la posibilidad de fallas en el examen por la menor cantidad de electrodos adheridos al cuerpo del paciente. **Métodos:** Agrega la técnica del vetocardiograma al electrocardiograma vestible, que consta de tres derivaciones ortonormales Vx, Vy y Vz, midiendo los componentes dinámicos del vector cardíaco. **Resultados:** La visualización del biopotencial cardíaco en la aplicación web-móvil representa satisfactoriamente la visualización de las doce derivaciones sintetizadas a partir de la transformada de Dower, así como las proyecciones espaciales del bucle cardíaco bajo una vista tridimensional. **Conclusión:** Viabilidad de integrar el vetocardiograma con el examen electrocardiográfico.

[1] *Master's Student. Postgraduate Program in Electrical Engineering (PPGEEL), Federal University of Santa Catarina - UFSC, Florianópolis, (SC), Brazil.*
[2] *Master's Student. Postgraduate Program in Energy and Sustainability Engineering (PPGES), Federal University of Santa Catarina - UFSC, Araranguá, (SC), Brazil.*
[3] *PhD, Professor of Computer of Department (DEC), Federal University of Santa Catarina - UFSC, Araranguá, (SC), Brazil.*

Autor Correspondente: **Vinícius Rodrigues Zanon**
e-mail: **vinicius.zanon@posgrad.ufsc.br**

Artigo recebido: **17/09/2021**
Aprovado: **15/03/2022**

INTRODUCTION

According to the World Health Organization (WHO), cardiovascular diseases (CVDs) represent 32% of all causes of death worldwide. In 2019, It was estimated that 17.9 million people died with a diagnosis related to heart disease[1]. For beginning the treatment with medical assistance, CVDs must be detected as soon as possible. In the current context of the COVID-19 pandemic, the situation is even more worrying, referring to the cardiovascular sequelae affected by respiratory disease[2]. It remains a mystery how the virus attacks the heart and blood vessels. Still, articles show this damage as a typical sequel to the infected, who have recovered from the disease in the scientific literature. A recently published article[3] by "JAMA Cardiology" pointed to cardiac damage in nearly 20% of the 416 patients hospitalized at the beginning of COVID-19 in Wuhan, China. The virus can directly attack the heart and blood vessels lining, rich in receptors known as ACE2 (Angiotensin Converting Enzyme 2). By altering the balance of these hormones responsible for regulating blood pressure, the virus can constrict the lungs' blood vessels. Another possibility is that a lack of oxygen can directly damage blood vessels due to the havoc wrought in the lungs. Or even that a storm of cytokines can devastate the heart as they do with other already identified organs[4].

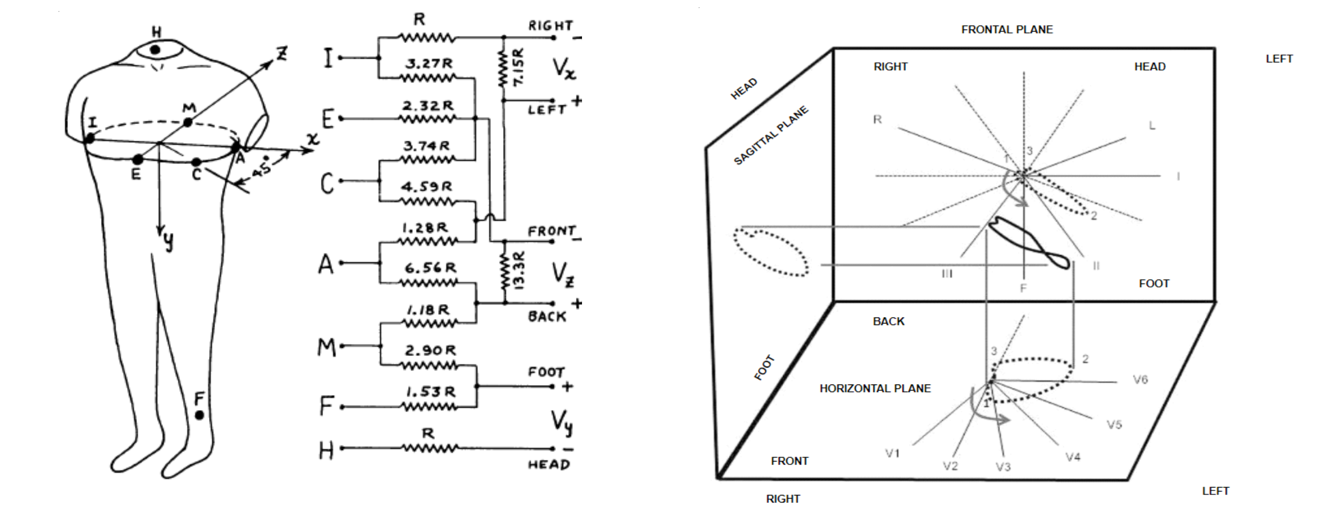
One of the feasible means of risk prevention and evaluation of cardiac events is monitoring the cardiac status of patients through the electrocardiogram (ECG) examination[5]. The ECG exam can be performed at rest, on the move (by a treadmill/bike), or through Holter monitoring (continuous monitoring for 24 hours at home). Although the ECG exam is well established in the medical field, researches show that the methodological procedure on its execution can compromise the clinical diagnosis of patients. The main problem presented in the literature points to the lack of knowledge of the correct positions of the electrodes on the patient's body, primarily by non-medical health professionals[6]. In the first study, 80% of the electrode connections were placed in patients incorrectly and, in the second, only 1% got it right. Incorrect links of the electrodes can lead to mistakes in capturing and interpreting the clinical results of the electrocardiogram[7].

This article proposes a wearable vest capable of conditioning cardiac signals from three simultaneous channels using the orthonormal derivations Vx, Vy, and Vz, presented by Frank's central derivation. The 12 electrocardiogram derivations are obtained from three channels provided by the vectorcardiogram (VCG) using the Dower transform. This strategy allows the reduced use of derivations in clinical practice. Also, it minimizes the professional's chance of making mistakes in the exam due to the smaller number of electrodes attached to the patient's body.

Obtaining the ECG and VCG embedded in the wearable vest serves as a diagnostic tool for the heart's electrical activities under a temporal and spatial view along three orthogonal planes of the body. The absence of spatiotemporal resolution in conventional ECG representations restricts medical interpretation and clinical use. This analysis perspective can show cardiac pathological patterns that may not be detectable in traditional electrocardiograms[8]. Thus, the wearable vest contributes to state-of-the-art to favor a complete clinical diagnosis, mitigating the lack of information in situations where the electrocardiogram is not enough.

MATERIALS AND METHODS

Conventional single-derivation ECG signals detect only a temporal view of excitation and propagation of cardiac electrical activities. Multi-derivation ECG systems such as the 12-derivation ECG used extensively in clinical applications are designed to visualize the heart's electrical activities multi-directionally. However, much of this information can be redundant. Only a tiny fraction of captured data is used for analysis by physicians, which is often analyzed based on experience, specializations, and memorization of ECG signals for different cardiac pathologies. This is challenging, and cardiologists constantly



(a) (b)

Figure 1 - a) Orthonormal Derivations X, Y, Z, taken from Ernest Frank[9] ; b) Projection on 3 Spatial Planes, taken from Pastore et al.[8]11 12,5

look for more accurate and effective alternatives.

In this sense, an alternative to the 12-derivation ECG is the vetocardiogram. It consists of three orthonormal derivations (Vx, Vy, and Vz), with derivation vectors in the directions of the main (orthogonal) axes of the body and with equal (normalized) electrode forces, thus measuring the dynamic components x, y, and z of the heart vector, respectively, as follows in figure 1 (a).

The VCG has some advantages when compared to the ECG. However, when analyzed together with the 12-derivation ECG, they can help in different situations that are very common in clinical practice. Figure 1 (b) demonstrates the heart's electrical activation and its projection in the three spatial planes, originating the vetocardiographic projections in the respective planes. Thus, the three-dimensional spatial orientation of atrial and ventricular activities creates a complete observation tool, providing an essential gain in the differential diagnosis of some pathologies.

System Overview

Figure 2 is a block diagram that shows the functional blocks defining the system's architecture in this project. These blocks were named input interface, processing interface (analog and digital), output interface, and power system.

The input interface is formed by the ECG capture sensors (electrodes) embedded in the wearable vest. Thus, the electrodes will be placed on the human body, using the derivations proposed by Frank, which record the potential difference between electrodes located in different planes (frontal, horizontal, and sagittal).

An instrumentation amplifier with a high common-mode rejection ratio (CMRR) forms the analog cardiac signal conditioning system. The inputs are the three signals that constitute the derivations Vx, Vy, and Vz, coming from the frontal, horizontal and sagittal planes, all referenced to the ground (GND). The noise, common to both inputs, is effectively eliminated. For the circuit to provide quality output, care was needed regarding noise from parasitic sources. Therefore, an isolation protection circuit was used, providing the patient with a low risk of electrical shock caused by possible unwanted impedances and filtering techniques to eliminate radio frequencies and over-voltages.

The system is also responsible for filtering the bioelectrical signal acquired by the instrumentation amplifier. The designed analog filters are anti-aliasing (500Hz), high-pass (0.05Hz), and Notch (50Hz) low-pass. The filters guarantee the frequency spectrum of the cardiac signal without interference. After the filtering step, an offset voltage is set to correct the DC level compatible with the microcontroller.

Finally, in the power system, a 9V battery and voltage regulators are used as a power source to supply the operating voltages that the processing interface needs.

Input Interface: Wearable Vest

The input interface consists of ECG capture sensors embedded in the wearable vest. The sensors used to capture the cardiac signal connected to the wearable interface are conventional silver surface electrodes (Ag/AgCl). To

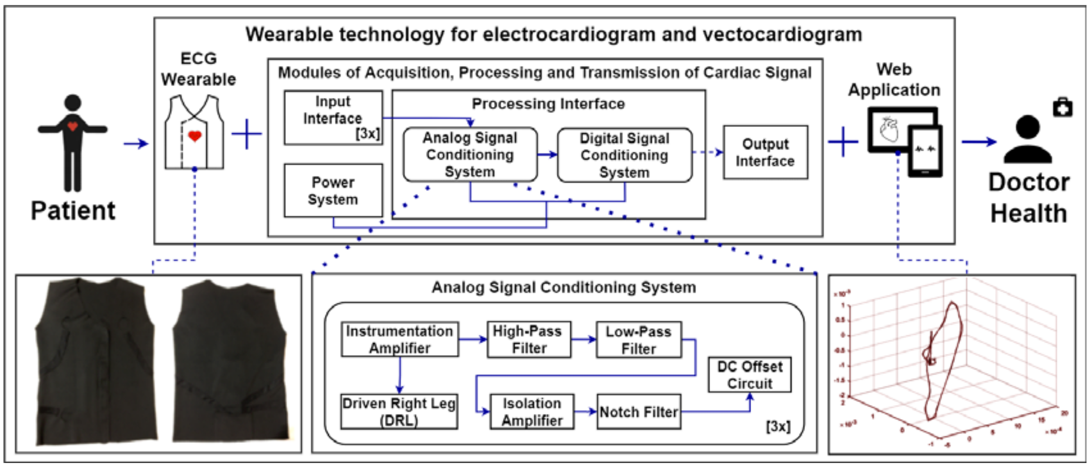


Figure 2 – Block Diagram System Architecture.

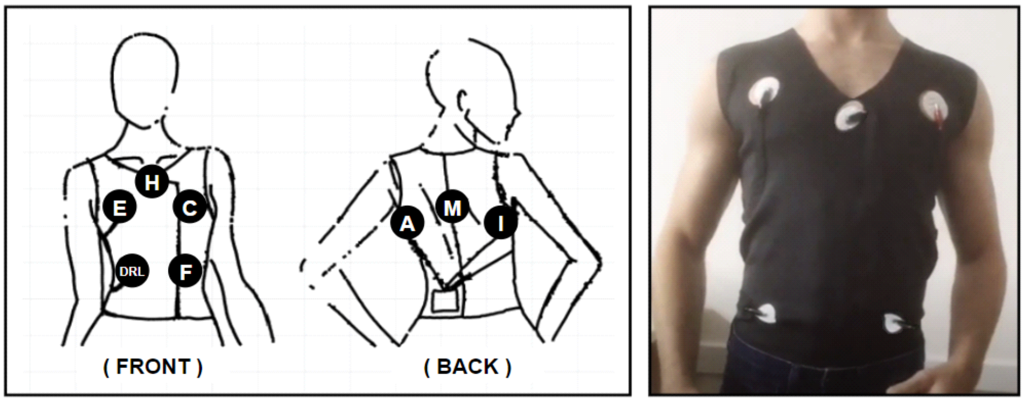


Figure 3 – Wearable Vest

embed the sensors, branches in fabric strips correctly route Frank's derivation.

Furthermore, in search of textile technologies that meet the requirements of comfort and well-being, the Neoprene fabric was chosen to fabricate the vest. The material has relevant technical properties, such as elasticity, low deformation, isothermal property, and impermeability[10]. Finally, a pocket was built in the wearable vest to attach the processing device to the vest. Figure 3 shows the sketch and execution of the wearable interface.

Processing Interface: Analog and Digital Systems for Acquisition of Cardiac Signal

As illustrated in the system architecture block diagram (figure 2), the Processing Interface comprises analog and digital signal conditioning systems. The analog conditioning circuit is mainly based on the following elements: instrumentation amplifier, analog filters, electrical protection/isolation circuits, offset circuit and driven right leg circuit (DRL).

As bioelectrical signals are comprised in the range of microvolts to millivolts (cardiac signal from 0.5 to 4mV), it is necessary to use an instrumentation amplifier more efficiently, subject to interference and noise of different natures. The instrumentation amplifier adopted for developing the ECG signal conditioning circuit is the INA129E. It features high input impedance (10MÙ), low output resistance, high CMRR (93dB), and low offset voltage at the output (50uV). The amplification circuit was configured for a gain of 100 times the input signal.

In addition, it was necessary to design and implement an active high-pass filter (to remove unwanted DC levels) with a cutoff frequency of 0.05Hz and a fourth-order anti-aliasing low-pass filter with a cutoff frequency of 500Hz. Also, a Notch-type filter with quality factor Q = 0.7 was designed to eliminate electromagnetic noise from the electrical network. In figure 4, it is possible to visualize the amplification circuit and the filters used for the conditioning of the cardiac signal.

The driven right leg circuit, shown in Figure 5, was implemented to ensure that maximum noise is rejected. The common-mode signals (extracted from the instrumentation amplifiers) are added, inverted, and applied to the patient. This approach is a weighted integrator ampli-

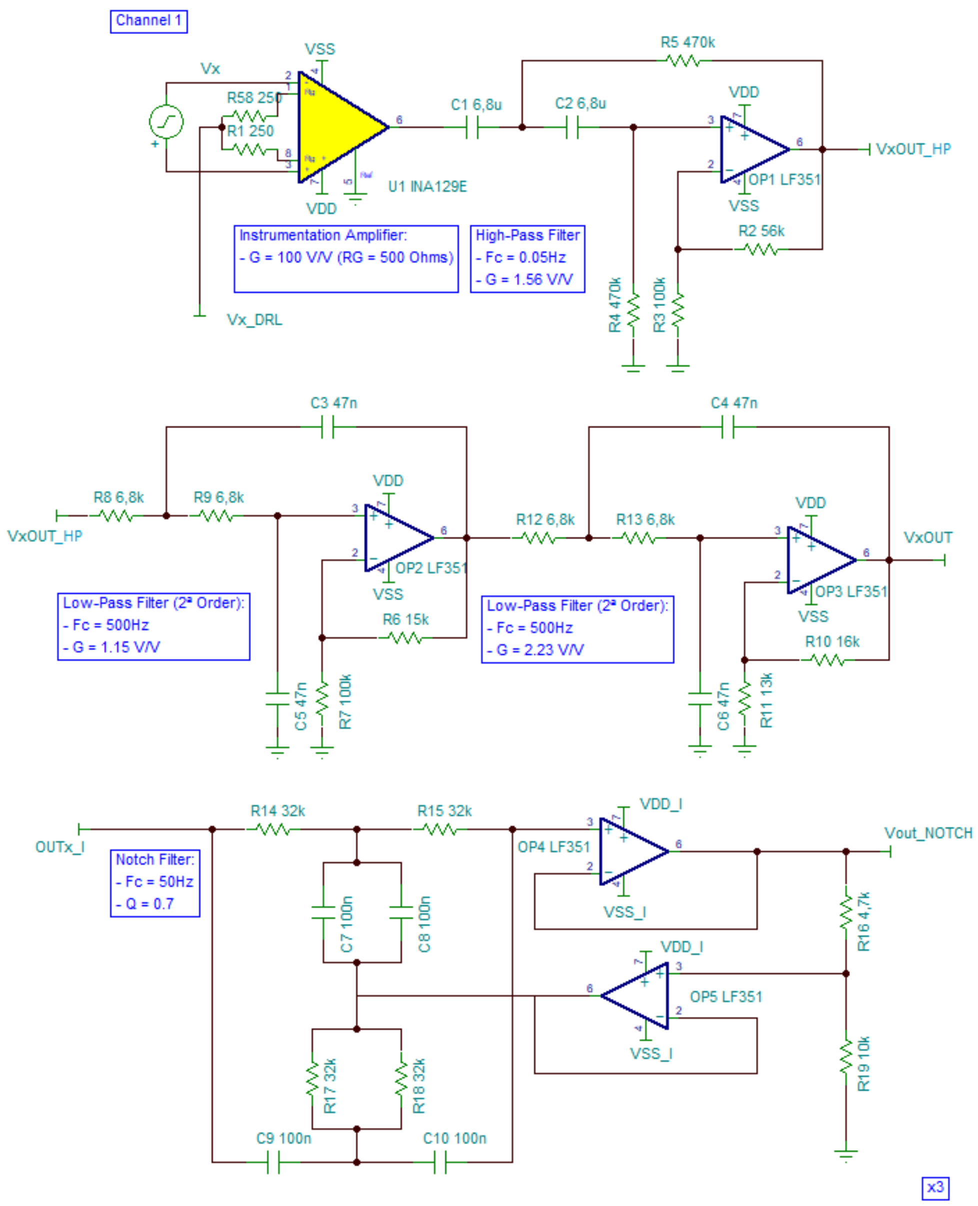


Figure 4 – Analog Amplification Circuit and Filters.

fier topology, whose output is proportional to the integral of the weighted sum of the three inputs Vx, Vy, and Vz.

Furthermore, as the microcontroller does not operate with negative analog input voltages, it was necessary to implement an offset circuit that includes a DC voltage level to the cardiac signal conditioned using the INA129E (Instrumentation Amplifier). In this case, an operational amplifier configured in buffer mode with unity gain was used to isolate and increase the cardiac signal to a voltage of 500 mV.

In addition, a voltage isolating circuit using the ISO121 precision amplifier has been included. This circuit isolates the monitored patient's power supply, providing minimal risk to the user. After conditioning the cardiac signal made by the analog system, it must be processed, stored, and made available in an application for data visualization. The digital conditioning system consists of an analog-digital converter (ADC) responsible for processing the analog inputs. The wireless communication system is embedded in the ESP32 microcontroller, comprising a WiFi communication peripheral.

With the signals adequately processed, a web application was created that provides the data instantly to the end-user on an ECG monitor. The application allows the user to export or import graphics in image format and datasheet, to be stored in a repository present on the access device and also sent, by application, to the email of the previously registered cardiologist. Access to the web application can be performed from any device (smartphone or computer) with wireless capability. In addition, it is possible to view the cardiac graph from a 12-derivations perspective (electrocardiogram) and the spatial representation of the cardiac signal (vectorcardiogram).

RESULTS AND DISCUSSION

With the end of the development of the wearable system, it was possible to move on to the critical tests and analysis stage to verify the results achieved.

After the signals obtained from the Frank derivation (Vx, Vy, and Vz) were amplified, filtered, and conditioned by analog instrumentation, the Dower transform was performed to acquire eight of the twelve derivations in the digital processing required by the conventional electrocardiogram.

Although several methods have been proposed to synthesize VCG from 12-derivation ECG, inverse Dower matrix transformation is the most commonly used[11]. The transformation operation to obtain eight independent electrocardiogram derivations is given by equation (1):

$$ECG_{[8x1]} = M_{D\ [8x3]} \times VCG_{[3x1]} \qquad (1)$$

Where, $ECG_{[8x1]}$ is a matrix resulting from the eight cardiac derivations (V1, V2, V3, V4, V5, V6, D1, and D2). The matrix $VCG_{[3x1]}$ contains Frank's derivation inputs (Vx, Vy, and Vz), and the inverse Dower matrix $M_{D[8x3]}$ represents the multiplicative factors of the linear

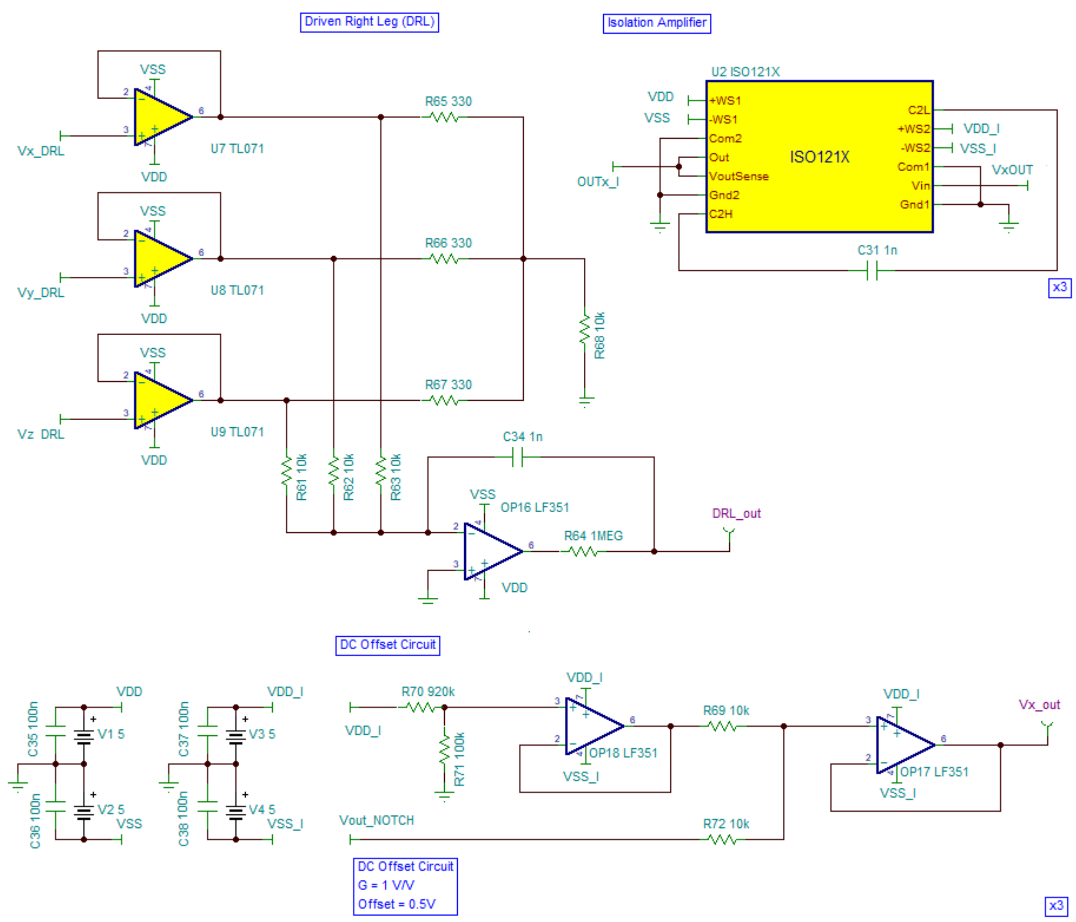


Figure 5 – Driven Right Leg, Isolation Amplifier and Offset Circuits.

transformation applied to the inputs. The matrix used follows below:

$$M_D[8 \times 3] = \begin{bmatrix} -0.515 & 0.157 & -0.917 \\ 0.044 & 0.164 & -1.387 \\ 0.882 & 0.098 & -1.277 \\ 1.213 & 0.127 & -0.601 \\ 1.125 & 0.127 & -0.086 \\ 0.831 & 0.076 & 0.230 \\ 0.632 & -0.235 & 0.059 \\ 0.235 & 1.066 & -0.132 \end{bmatrix}$$

The only derivations that do not result from the Dower transform are the augmented leads aVR, aVL, aVF, and derivation D3. We used Kirchhoff's Laws of voltages as a function of limb derivations (D1 and D2) to find them. Derivation D3 can be obtained from equation (2):

$$D1 + D3 - D2 = 0 \quad (2)$$
$$D3 = D2 - D1$$

The derivations aVR, aVL and aVF are obtained from the potential difference between two electrodes (lead) placed on the right arm, left arm, or left leg. Furthermore, they are obtained by the average voltage of the shunt opposite this potential difference, as shown in Figure 6. The average is made through the resistors R on the inverting input of the amplifier, and the resistor R/2 is used to match the non-inverter input impedance of the amplifier.

In the aVL acquisition configuration, the Kirchhoff mesh is considered passing through derivation I and through half of derivation two, as in equation (3):

$$aVL - D1 + (D2 / 2) = 0 \quad (3)$$
$$aVL = D1 - (D2 / 2)$$

Likewise, the other two augmented derivations aVR and aVF can be obtained in equations (4) and (5):

$$aVR = -(D1 + D2) / 2 \quad (4)$$
$$aVF = D2 - (D1 / 2) \quad (5)$$

With all twelve cardiac derivations synthesized from Frank's signals in the digital processing stage, the wearable vest was submitted to an individual to test the system's functionality and obtain the electrocardiogram and vetocardiogram graphics via a web-mobile application, implemented in the interface of exit from the system.

The cardiac signals captured by the wearable vest elec-

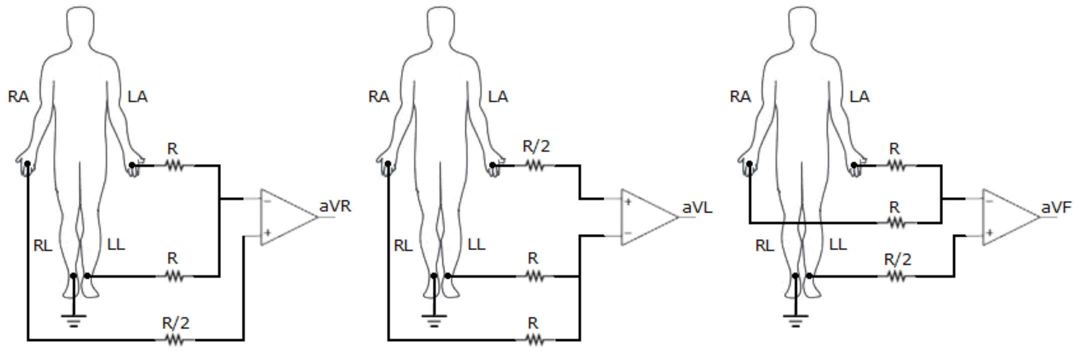


Figure 6 - Derivation Circuit aVR, aVL, aVF.

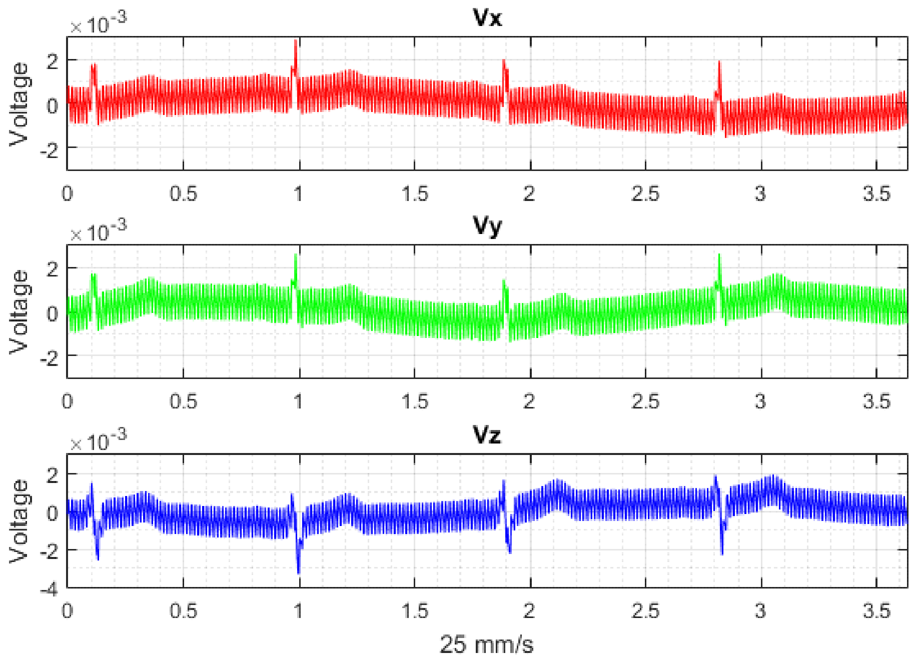


Figure 7 – Vectorcardiogram (3-Derivation Frank)

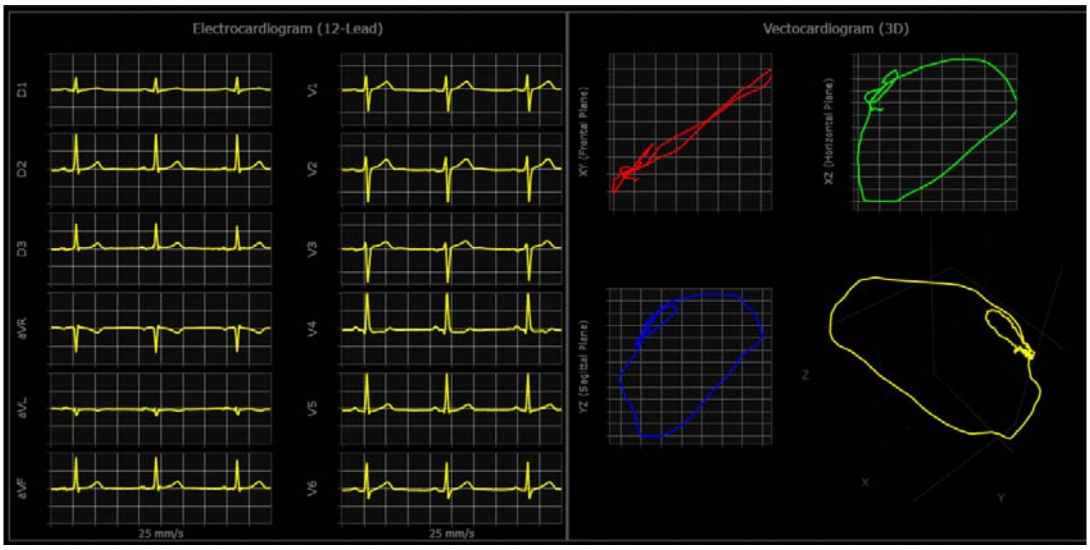


Figure 8 – Output interface: Cardiac Signals processed by the Web Application

trodes are shown in Figure 7. The presence of electromagnetic and bioelectrical noises is noticeable, in addition to the baseline shift of the Vx, Vy, and Vz signals.

After conditioning the signs with the wearable vest, it is possible to visualize the cardiac graphs for the ECG and VCG exams. Figure 8 shows the implemented web application, which shows the electrocardiogram exam's twelve derivations (yellow signs). And in a 3D perspective, the frontal, lateral and sagittal planes correspond to the signals of the vectorcardiogram for a cardiac loop (red, green, and blue). A cardiac loop can be understood as the temporal tracing of the cardiac record under a spatial view (x, y, and z axes) with views in the XY, XZ, YZ, and XYZ planes for a heartbeat window.

CONCLUSION

From developing the wearable vest prototype, it was possible to understand the variables that covered the project and the circuit and processing necessary for the acquisition of the cardiac signal in electrocardiogram and vetocardiogram exams. The display of the cardiac biopotential in the web-mobile application satisfactorily represents the visualization of the twelve derivations synthesized from the Dower transform and the spatial projections of the cardiac loop under a three-dimensional view.

This visualization introduces the feasibility of integrating the vetocardiogram with the electrocardiogram exam, bringing rich information that could not be analyzed before on the conventional ECG exam in a spatial and temporal view, improving the clinical diagnosis.

In addition, the wearable vest has characteristics consistent with solving the problem of performing the electrocardiogram exam since obtaining the twelve derivations using only the three derivations proposed by Frank. This reduces the effects caused by the mistaken diagnosis given by the healthcare professional's lack of knowledge of the electrode connections in the patient's body.

It is a wearable that transmits data remotely, through a web application, accessed on any device with WiFi wireless communication. It is possible to imagine its use, mainly from the context of the COVID-19 pandemic, for the remote monitoring of patients who present sequelae of the disease with cardiac pathologies.

Finally, future work intends to develop safety modules for the wearable vest and associate processing with AI techniques for processing information, making it a wearable, wireless, and intelligent device. Both studies are underway at the Federal University of Santa Catarina.

REFERENCES

1. WHO - Cardiovascular diseases (CVDs) [Internet]; [cited 2021 Jun 11]. [Accessed 2021 Jul 15]. Available from: https://www.who.int/en/news-room/fact- sheets/detail/cardiovascular-diseases-(cvds)
2. Gemelli Against COVID-19 Post-Acute Care Study Group, Post-COVID-19 global health strategies: the need for an interdisciplinary approach. Aging Clin Exp Res, 2020; 32:1613–1620. DOI: 10.1007/s40520-020-01616-x.
3. Carfì A, Bernabei R, Landi F, Persistent Symptoms in Patients After Acute COVID-19. JAMA – Journal of the American Medical Association, 2020; 324(6):603–605. DOI: 10.1001/jama.2020.12603.
4. Wadman M, Couzin JF, Kaiser J, Matacic C, A rampage through the body. Science, 2020; 368(6489):356–360. DOI: 10.1126/science.368.6489.356.
5. Passo SJG, Oliveira HS, Pinto RA, Quispe KGM, Gusti R, Souto EJP, Classificação de Arritmias com Paradigma Inter e Intra Paciente utilizando Aprendizagem Profunda. J. Health Inform, 2020; 352(7): 352-357.[Accessed 2021 Jul 20]. Available from: http://www.jhi-sbis.saude.ws/ojs-jhi/index.php/ jhi-sbis/ article/view/838/441
6. Monteiro NO, Marçal DC, Bitencourt IF, Rocha LS, Dias EC, Habilidades dos Enfermeiros na Realização e Interpretação do Eletrocardiograma em Pronto Atendimento. Rev SIMPAC, 2018; 10(1): 1122-1126. [Accessed 2021 Jul 17]. Available from: https://academico.univicosa.com.br/revista/index.php/RevistaSimpac/article/view/1197/1264
7. Fernandes LS, Lira MC, França VV, Valois AA, Valença MP, Conhecimento Teórico-Prático de Enfermeiras sobre Eletrocardiograma. Rev Baiana de Enfermagem, 2015; 29(2): 98-105. DOI: 10.18471/rbe.v29i2.12654.
8. Pastore CA, Samesima N, Filho HGP, Tobias NMMO, Madaloso BA, Facin ME, Aplicabilidade do

Eletrovetorcardiograma na Atual Prática Clínica – Um Retrato Preciso da Ativação Elétrica Cardíaca. Arq Bras Cardiol, 2019; 113(1):87-99. DOI: 10.5935/abc.20190095.
9. Ernest F, An Accurate Clinically Practical System for Spatial Vectorcardio- graphy. Circulation, 1956; 13:737-749. DOI: 10.1161/01.CIR.13.5.737.
10. THOMAS - All About Neoprene- Properties, Uses and Applications [Internet]; [Accessed 2021 Jul 15]. Available from: https://www.thomasnet.com/ articles/plastics-rubber/traits-applications-neoprene/
11. Edenbrandt L, Pahlm O, Vectorcardiogram synthesized from a 12-lead ECG: Superiority of the inverse Dower matrix. Journal of Electrocardiology, 1988; 21(4):361-367. DOI: 10.1016/0022-0736(88)90113-6.