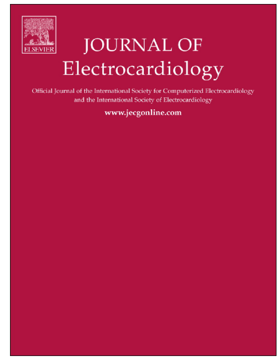
Journal Pre-proof



Comparison of spatial temporal representations of the vectorcardiogram using digital image processing

Ittalo dos Santos Silva, José Raimundo Barbosa, Rafael Duarte de Sousa, IgorFranklin Brito de Souza, Renato de Aguiar Hortegal, Carlos Danilo Miranda Regis

PII: S0022-0736(19)30906-9

DOI: https://doi.org/10.1016/j.jelectrocard.2020.02.013

Reference: YJELC 53015

To appear in: *Journal of Electrocardiology*

Comparison of spatial temporal representations of the vectorcardiogram using digital image processing

Ittalo dos Santos Silva[a], José Raimundo Barbosa[a], Rafael Duarte de Sousa[a,*], Igor Franklin Brito de Souza[a], Renato de Aguiar Hortegal[b], Carlos Danilo Miranda Regis[a].

[a] Federal Institute of Paraíba, João Pessoa, PB, Brazil

[b] Dante Pazzanese Institute of Cardiology, São Paulo, SP, Brazil

*Corresponding author at: Federal Institute of Paraíba, Av. Primeiro de Maio, 720 João Pessoa, PB, Brazil. E-mail address: jsraimundob@gmail.com .

Abstract

Introduction: The vectorcardiography (VCG) is a method of representing the heart's electrical activity in three dimensions that is not frequently used in clinical practice due to the higher complexity compared to electrocardiography (ECG). A way around this problem was the development of regression techniques to obtain the VCG from the 12-lead ECG and the evaluation of these techniques is done by comparing the parameters obtained by the gold standard method and by the VCG obtained by the alternative methods. In this paper it is proposed instead a comparison between the images of the VCG planes using the values returned by digital image processing metrics such as PSNR, SSIM and PW-SSIM.

Methods: The signals used were obtained from the Physikalisch-Technische Bundesanstalt Diagnostic ECG Database, which contains both the VCGs obtained by the gold standard method and the 12 lead ECG signals. They were divided into five groups that contained a control group and according to the region of the wall infarction. The ECG signals were then filtered using a Butterworth Finite Impulse Response bandpass filter, with cutoff frequencies of 3 Hz and 45 Hz and then the VCGs were by a computer application using the Kors inverse matrix method, the Kors quasi-orthogonal method and the Dower Inverse Matrix method. The reconstructed signals were then compared using the PSNR, SSIM and PW-SSIM methods. The returned values were presented in tables for each group containing the average value and standard deviance for each method in each VCG plane.

Results: Using image processing techniques, it was possible to perceive that the alternative methods to obtain the VCG have a high confiability that could be compared to the gold standard in signals from healthy subjects. However, signals from pathological subjects present variations that could be caused by a deficit of these alternative methods to represent the pathology in these cases. Considering the PW-SSIM, the Frontal plane by the reconstructions was considered the most similar to the gold standard, having PW-SSIM values higher than 0.93 and for the Horizontal plane two groups had PW-SSIM values lower than 0.90 and for the Sagittal plane all groups had values lower than this value.

Discussion: The values yielded by the PSNR and SSIM had low variance, worsening the perception of the effect of the reconstruction method used or the infarction effect over the reconstruction. The values lower than 0.90 could indicate that these planes have their generation most affected by the infarction.

Conclusion: The three methods of obtaining the VCG Frank leads, the Kors Quasi-Orthogonal method, the Kors Linear Regression method and the Dower Inverse Matrix, presented differences in the metrics: PSNR, SSIM and PW-SSIM in normal subjects according to the planes frontal, horizontal and sagittal and in subjects with Myocardial Infarction according to its topography: anterior, inferolateral, inferior or multiarterials. Considering only the PW-SSIM, the QO method had the best performance in different signals, followed by the Dower method.

Keywords: PSNR, SSIM, PW-SSIM, Vectorcardiography, Digital Image Processing.

Introduction

The vectorcardiogram (VCG), the result of the vectorcardiography, is an examination method first described in 1920 [1][2] and a method of representing in three dimensions the electrical activity of the heart based on the records made by three bipolar leads, called vectors, that are intersected at 90 degrees between themselves. Because of that, they are also known as orthogonal leads. The morphology of the measurements obtained by these leads has three loops: the P loop, the QRS loop and the T loop; that allow the evaluation of the cardiac cycle from different perspectives corresponding to each plane from the Euclidean space (XY, XZ, YZ), whereas each of these planes corresponds to the fundamental planes of the human body (frontal, horizontal and sagittal), respectively [3].

A simpler method used to record the electrical activity of the heart is the electrocardiogram (ECG), in which the variations of the electrical potential in the heart are measured using electrodes distributed on the skin in certain areas of the body. The advantage of the VCG over the ECG is the fact that it offers 3D parameters not available in standard ECG exams. Thus, it offers more diagnostic and prognostic value [3].

In 1956, Frank proposed what would later be considered the gold standard VCG acquisition method. His system consists of seven electrodes placed over the body in a very specific way. Although it presents many advantages compared to the methods that were used then to obtain the VCG, it still has disadvantages that prevent it from being used as a routine cardiac test, such as the need for specific hardware to measure the VCG; the need of the placement of the electrodes in specific locations, including the neck and the back, making it more difficult and more uncomfortable to be used in patients in supine position; and also requiring a higher level of training in the electrode placement and VCG analysis compared to ECG [3][4].

In order to find a compromise between the simplicity of the ECG and the additional parameters offered by VCG many efforts were made to reconstruct the VCG from the usual 12-lead ECG exams. These efforts resulted in the development of alternative computational methods of obtaining VCG such as the Kors regression matrix method, the Kors quasi-orthogonal method and the Dower's inverse matrix method, being the first and the third most common. From these two, the Kors Regression Matrix method yields the best results in the reconstruction of Frank's three lead signals [5 - 7].

Usually, the comparison between these methods is done using parameters extracted from the VCG curves obtained by the Frank's Method and by the alternative methods to evaluate the effectiveness of each method in a certain scenario [7]. However, in this paper, a different method of comparison is proposed. It is based on the assessment of images from each orthogonal plane of the 3D plot of the VCG (XY, XZ, YZ) using digital image processing metrics such as PSNR, SSIM and PW-SSIM, in order to determine which method is the closest, statistically, to the Frank gold standard.

Methods

The work presented in this paper is divided into four stages that were defined based on their significance. These stages are: obtaining the signals from the database; preprocessing the signals to standardize them and remove deformed or incomplete signals; extracting the images of planes of the Frank VCG leads and of the VCG obtained by the alternative methods from the 12 lead ECG; evaluation of the different regression methods using digital image processing techniques; and, finally, the analysis and discussion of the results. The Figure 4 shows part of the steps described above and later they are described in more detail.

[Figure 1]

Database

The ECG and VCG signals were extracted from the Physikalisch-Technische Bundesanstalt (PTB) Diagnostic ECG Database [8], which provides data from 290 subjects. Each set of files corresponding to a patient contain one or more exams (1-7 exams per patient file), which contains the standard 12 ECG leads and the X, Y, Z Frank leads, collected with a sampling rate of 1000 samples per second per channel. Eight of the standard ECG leads plus the orthogonal Frank leads were used for this study in order to perform both regression matrix of Kors and Frank methods, respectively.

The subjects were classified according to the infarcted wall/culprit vessel in: anterior wall Myocardial infarction (MI) or Left Anterior Descending artery severe obstruction/occlusion (group II a), inferolateral wall or Circumflex artery severe obstruction/occlusion (group II b), inferior wall MI or Right Coronary or Left Circumflex artery severe obstruction/occlusion (group II c), and bi/multiarterial disease patients (group III). The healthy subjects were classified as control group (group I). This clustering is shown on Table 1.

[Table 1]

Preprocessing

Each signal passed through a process of filtering, besides the filtering that occurred in the ECG acquisition stage [9], performed in a similar manner as Silva [10], in order to remove undesired components of the signal considered as noise, such as muscle noise, and to make the baseline wandering correction. This process was based on a Butterworth Finite Impulse Response (FIR) bandpass filter, which had cutoff frequencies of 3 Hz and 45 Hz, and an order of 300. This filtering stage is responsible to reduce low frequency artifacts (the frequency is usually less than 0.5 Hz) on the signal caused by transpiration, breathing and body movements;

and to lessen the effects of the transmission lines interferences and muscular noise [11]. The cutoff frequency values used were obtained empirically, considering the values that best achieved the VCG usual shape [12].

VCG Reconstruction

After the filtering stage, the Frank VCG leads were ready for the next stage (since they came from the database) and the alternative methods to reconstruct VCG were developed by an application implemented in Python 3, according to the Kors inverse matrix method, the Kors quasi-orthogonal method and the Dower Inverse Matrix Method.

[Figure 2]

The electrical fields from the heart depolarization can be represented as vectors, in a way that the magnitude and direction of these forces can be shown through the fundamental planes of the human body: sagittal, frontal and transversal. These planes are equivalent to the VCG planes XZ, YZ and XY, respectively. The VCG is obtained as these vectors are projected on a cartesian axis system [2].

Frank method is the electrode placement system designed by Frank, also known as Frank VCG. It consists of seven electrodes in which one is placed on the back of the neck, five are distributed over the chest at the same transversal level in a distinctive placement and one is on the left leg as the standard electrode. Using these electrodes in these settings, it is possible to determine the electrical activity of the heart in three dimensions corresponding to projections over the planes of the human body with an optimum compromise, these projections are known as leads [4]. Since the three Frank orthogonal leads are already in the files obtained from PTB, no further processing is needed, except for the filtering stage, before plotting them as a VCG.

Currently, three different ways are used to obtain VCG leads from the standard 12 lead ECG. In the single lead approach, a VCG lead is represented by an ECG lead that has the closest resemblance using a scaling factor. In this case, from the 12 leads, only three, those corresponding to the VCG leads, will have scaling coefficients different from 0. According to Kors, the VCG leads X, Y and Z are best approached by the ECG leads V6, II and -0.5*V2, respectively [5]. This approach is known as the Kors Quasi-orthogonal method, from now on it will be referred as the quasi-orthogonal method or Kors QO.

Another way of obtaining a VCG lead from ECG is through a model-based approach, such as the one used by Dower, called Dower inverse matrix method. Initially, Dower used this model-based approach to obtain the 12-lead ECG from Frank VCG. Later, the inverse matrix from the one used by Dower in the former process was computed to reconstruct Frank VCG from the ECG [6].

The VCG can also be obtained from the ECG through linear regression techniques. In this case, the coefficients are found using a learning set of VCGs and ECGs, and minimizing the sum of the square differences between the original VCG lead and its reconstructed version. From now on this method will be referred as the Kors Linear Regression or Kors LR [5].

The coefficients of the matrices that are used to make the correspondence between the 12-lead ECG and Frank VCG are shown in Table 2.

[Table 2]

The application developed for the present work uses the ECG leads shown on Table 2 as input and then, the X, Y and Z leads are obtained based on a linear transform using the coefficients also shown in Table 3.

The VCG signals obtained by those methods were plotted by plane (XY, XZ and YZ). Before the image comparison, there was a redimensioning stage to 512 x 512px due to differences in the magnitude of the signals.

Image objective analysis

The objective analysis of the images allows the detection of subtle differences that are not perceptible by the human eye. Similarly, the method employed on this work detects the differences between the images generated by different methods, allowing the comparison of those alternative methods with Frank VCG, which is considered as the gold standard, and allowing their validation. This method consists of an algorithm that receives two sets of images corresponding to the VCG planes obtained by Frank and by an alternative method. Then an analysis of the equivalence of both methods is performed using the following objective metrics: PSNR, SSIM and PW-SSIM.

PSNR Metric

The Peak Signal to Noise Ratio (PSNR) is one of the most used metrics in image processing, due to its easy calculation and low computational cost [13 - 15]. This method expresses the maximum ratio of a given signal to the added noise, and is used to measure the structural quality of images. For this, it is necessary to formulate the mean square error for the digital representation of monochromatic images I and K of size m x n, the MSE is defined as,

$$MSE = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^{2} \quad (1)$$ [Equation 1]

Using the previous equation, the PSNR is represented by,

$$PSNR = 10 * \log_{10}\left(\frac{MAX_I^2}{MSE}\right) = 20 * \log_{10}\left(\frac{MAX_I}{\sqrt{MSE}}\right) \quad (2)$$ [Equation 2]

in which MAX indicates the maximum possible pixel value in an image.

The Equation 2 results in a value between 0 and ∞. In the literature, a range between 0 and 50 is usually used to limit the representation of the range of PSNR values, with 0 being the worst case and 50 being the best.

SSIM Metric

The Structural Similarity Index (SSIM) is based on the assumption that the human visual system is highly adapted to extract structural information from images [15]. Therefore, each pixel has a strong dependence on the others and this dependence increases with the proximity. This dependence presents an important information about the structure of the objects in the image and quantifies the structural change of an image as a good approximation to the perceived quality [14].

To identify the structural information, the SSIM metric uses a statistical approach based on the average luminance and $n_x n$ block contrast of the image. The mean (μ), standard deviation (σ^2) and covariance (σ_{fg}) are calculated for each block, the mean and standard deviation are estimates of the luminance and contrast of the image, respectively. Covariance is a measure of how much a signal is different from the other.

The SSIM uses the measure of structural distortion rather than the error itself. If $x = \{x\ i \mid i = 1, 2, . . ., N\}$ represents the original signal and $y = \{y\ i \mid i = 1, 2, . . ., N\}$ represents the distorted signal, in which i is the pixel index value. The structural similarity index can be calculated according to Equation 3 [17].

$$SSIM(x, y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)} \quad (3)$$ [Equation 3]

In the Equation 3, μ_x represents the average of x, μ_y represents the average of y. The variance of x is represented by σ_x^2 and the variance of y by σ_y^2. The $c_1 = (k_1L)^2$, $c_2 = (k_2L)^2$, are the variables to stabilize the division, $L = 2^{n-1}$ is the dynamic range of bits and $k_1 = 0.01$ and $k_2 = 0.03$ by default.

PW-SSIM Metric

The Perceptual Weighting Structural Similarity Index (PW-SSIM) uses a weighting-based approach to evaluate image quality, giving higher scores to visually more important regions [16]. For this, the magnitude of the gradient vectors of the original image is calculated using Sobel masks, then a frame is generated in which the pixel values are the magnitudes of the gradients. Thus, this frame is partitioned into blocks of 8x8 pixels, and for each block the Spatial Perceptual Information (SI) is calculated [17]. The SI is expressed by Equation 4.

$$\square\square = \left(\frac{1}{\square-1}\sum_{\square=1}^{1} (\square\square - \square)^2\}\right)^{\frac{1}{2}}(4)$$ [Equation 4]

in which, *N* is the number of pixels per blocks and $\square\square$ represents the average magnitude of the gradient in a block. Finally, PW-SSIM is computed using Equation 5,

$$\square\square - \square\square\square\square(\square,\square) = \frac{\sum_{\square=1}^{\square} \square\square\square\square_{\square}(\square,\square) * \square\square_{\square}}{\sum_{\square=1}^{\square} \square\square_{\square}}(5)$$ [Equation 5]

in which, *D* is the number of blocks, *f* is the representation of a 2D image and *h* represents a 2D degraded image.

Results

The results obtained in the objective image analysis are presented in this section and divided by groups corresponding to the region of infarction as presented in Table 1.

The Figure 3 illustrates the comparison between the XZ planes of the VCG obtained by Frank acquisition method and of the VCG reconstructed by Kors LR. Besides the agreement of the visual aspects, according to the values of PSNR and SSIM, both images are quite similar, since the SSIM value is close to 1, as it is shown in the tables below. Furthermore, the T loop orientation was preserved as well as the QRS Complex general morphology, both parameters with high diagnostic value [7].

[Figure 3]

The Table 3 shows the average results and the standard deviance, grouped by method, for the Group 1 (healthy controls). The best results for each group and metric are highlighted. In this case, the planes XY and XZ obtained by Kors LR were the closest from their respective planes to Frank VCG, considering the PSNR and SSIM metrics. For plane YZ, the QO method yielded the best results for these two metrics. Considering the PW-SSIM, the QO method had the best results for planes XY and XZ and Dower's inverse matrix for YZ plane.

[Table 3]

The results for the Group II.a (anterior wall MI), shown in Table 4, also point to the idea that the quasi-orthogonal method is considered by all metrics as the closest to the gold standard, considering only the plane XY. However, taking the plane XZ into account, each metric pointed for a different method of obtaining the VCG.

When the comparison was on the planes YZ, the PSNR and SSIM converged on their results, pointing the Kors Quasi-Orthogonal method as the closest from Frank Method. On the other side, the PW-SSIM pointed the Kors Linear Regression method as the most efficient.

[Table 4]

The Table 5 shows the results for the Group II.b (inferolateral wall infarction). The data reinforces the idea that the wall infarction influences the evaluation by plane. All the metrics considered that the Dower method leads to the best regression when only the XZ plane is considered. The Dower method also yielded the best results to the plane YZ in the metrics PSNR and SSIM. For the plane XY, the PSNR and SSIM pointed that Kors LR is the best method.

The results of the PW-SSIM show that the Kors QO method is the most adequate for reconstructing the VGC planes XY and YZ, thus differentiating itself from the other metrics. It is also shown that the YZ plane is the most different compared to Frank Method, since all the other values are below than 0.9.

[Table 5]

For the Group II.c (inferior wall infarction), shown in Table 6, when the evaluation considers the planes XY and XZ, all the metrics converged in their classifications, pointing both Kors QO and Dower inverse matrix as the best models to obtain the VCG, respectively for each plane. The inferior wall has direct impact in the values returned by the metrics when the lead Vx is involved. On the other hand, the PSNR and SSIM diverge from the PW-SSIM when the plan YZ is involved. Since this plane offers a longitudinal perspective of the VCG, even subtle changes may have great effects in the metrics, explaining this divergence.

[Table 6]

The Group III (multiarterial disease), which the results are shown in the Table 7, had the best results when the VCG was obtained using Kors QO method. However, when the planes XZ and YZ were considered, even though the PSNR and PW-SSIM still pointed Kors QO as the best method, they diverged from the SSIM, that pointed Dower's Inverse matrix as the most similar to Frank's VCG. Still, the difference between the results was minimal.

[Table 7]

Discussion

The metrics PSNR and SSIM are used mostly because they are the main metrics in image analysis, and thus used as reference, even though the PSNR performs poorly in some comparison cases [14]. In this work, the values returned by the PSNR and SSIM did not have a high variance (Figure 4), so the effect of the different methods used and presence or region of the infarction could not be noticed easily.

[Figure 4]

The PW-SSIM was chosen due to its capability of observing the most divergent regions in the images, since it considers the difference between the homogenous and transition parts, the white background and the lines, respectively, that is, the morphology of the curves. The Figure 5 shows that the PW-SSIM value changed for each method and each group, having a higher variance in certain planes depending on the region of the infarction. Thus, from now on only the PW-SSIM will analysed.

[Figure 5]

The PW-SSIM values, generally, are reduced from the Group I (Healthy signals) to the others (Pathological signals) and the plane in which this reduction occurs depends on the infarction region and the regression method employed. For the former, the values returned by this metric had shown that the Kors QO method had the best performance due to the higher average values and smaller standard deviance compared to the Kors LR.

For the pathological signals, the Group II.a (anterior wall MI), both methods by Kors were pointed as the best regression methods since they had the highest average value. However, XY plane obtained by all methods had the highest values, which could indicate that this plane is less affected by the infarction.

The Group II.b (inferolateral wall MI) did not have a regression method clearly pointed as the most adequate, but considering only the XY and XZ planes, Dower's method had the highest values and the plane YZ was the most different (had the smallest values) from the others.

The lower values yielded in the YZ plane for the Group II.c (inferior wall MI) also suggest that this plane has its generation most affected by the infarction. From a visual analysis in Figure 5, Dower's had the best performance. However, the planes obtained by this method did not follow the pattern found on the other methods, in which the PW-SSIM values fall from the XY to the XZ and YZ, respectively. A high difference can be noticed in the data obtained from this metric considering the planes that are affected by the pathology. The plane XY has a similarity value below 0.9 for Dower's method, whereas for Kors QO this value is above 0.9. These results are inverted for the plane XZ, where Dower's method has better performance than the QO.

For the Group III (multiarterial disease), the data indicates that Kors QO is the best method to obtain the VCG from the 12 lead ECG, followed by Kors LR. Since the infarctions occurs in multiple arteries, it is not possible to identify which plane is the most affected. This effect is noticed on the results presented in Table 7, where a high variation between Frank and the other methods is present in all planes and only in one case the similarity value was higher than 90%.

Comparing only the best results from all methods, for the plane XY, all the PW-SSIM values were higher than 0.93, meaning that it has a high similarity with Frank's method. For the plane XZ, two groups had PW-SSIM values below 0.90 and for the YZ, all the groups had these values below this threshold. This could indicate that this plane has its regression the most affected by the infarction.

The analysis presented in this paper differs from other groups in two main aspects: 1) the use of the imaging processing techniques which may fit better the issues related to raw data processing as well as the application of machine learning techniques and 2) the impact of the myocardial damage topography in these correlations among the different matrices.

This is pertinent because the anomalies perceived by the digital image processing algorithms could be the result of imperfections in the regression methods, reducing their usefulness in certain scenarios. These anomalies, that is, the variance of the metrics results in the planes of pathological signals may represent a deficit of the evaluated methods to perceive and present a pathology. More detailed studies are needed to confirm this hypothesis.

The presented findings are in partial agreement with the literature, that says that the correlation between the methods here shown is higher for Kors LR and Kors QO, respectively [18].

Conclusion

The three methods of obtaining the VCG Frank leads, the Kors Quasi-Orthogonal method, the Kors Linear Regression method and the Dower Inverse Matrix, presented differences in the metrics: PSNR, SSIM and PW-SSIM in normal subjects according to the frontal, horizontal and sagittal planes and in subjects with Myocardial Infarction according to its topography: anterior, inferolateral, inferior or multiarterials. Considering only the PW-SSIM, the QO method had the best performance in different signals, followed by the Dower method.

References

[1] MANN, Hubert. A method of analyzing the electrocardiogram. Archives of Internal Medicine, v. 25, n. 3, p. 283-294, 1920.

[2] BURCH, G. E.; ABILDSKOV, J. A.; CRONVICH, J. A. Vectorcardiography. Circulation, v. 8, n. 4, p. 605-613, 1953.

[3] MAHESHWARI, Sidharth et al. Frank vectorcardiographic system from standard 12 lead ECG: An effort to enhance cardiovascular diagnosis. Journal of electrocardiology, v. 49, n. 2, p. 231-242, 2016.

[4] FRANK, Ernest. An accurate, clinically practical system for spatial vectorcardiography. circulation, v. 13, n. 5, p. 737-749, 1956.

[5] KORS, J. A. et al. Reconstruction of the Frank vectorcardiogram from standard electrocardiographic leads: diagnostic comparison of different methods. European heart journal, v. 11, n. 12, p. 1083-1092, 1990.

[6] EDENBRANDT, Lars; PAHLM, Olle. Vectorcardiogram synthesized from a 12-lead ECG: superiority of the inverse Dower matrix. Journal of electrocardiology, v. 21, n. 4, p. 361-367, 1988.

[7] CORTEZ, Daniel L.; SCHLEGEL, Todd T. When deriving the spatial QRS-T angle from the 12-lead electrocardiogram, which transform is more Frank: regression or inverse Dower?. Journal of Electrocardiology, v. 43, n. 4, p. 302-309, 2010.

[8] GOLDBERGER, Ary L. et al. PhysioBank, PhysioToolkit, and PhysioNet: components of a new research resource for complex physiologic signals. Circulation, v. 101, n. 23, p. e215-e220, 2000.

[9] KLIGFIELD, Paul et al. Recommendations for the standardization and interpretation of the electrocardiogram: part I: the electrocardiogram and its technology a scientific statement from the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society endorsed by the International Society for Computerized Electrocardiology. Journal of the American College of Cardiology, v. 49, n. 10, p. 1109-1127, 2007.

[10] SILVA, Ittalo S. et al. Assessment of the Similarity Between Vectorcardiogram Curves of Both Methods Frank Standard and Kors Regression Matrix Using Digital Image Processing. In: XXVI Brazilian Congress on Biomedical Engineering. Springer, Singapore, 2019. p. 65-68.

[11] TSAI, Chung-Han; HSIEH, Zong-Han; FANG, Wai-Chi. A low-power low-noise cmos analog front-end ic for portable brain-heart monitoring applications. In: 2011 IEEE/NIH Life Science Systems and Applications Workshop (LiSSA). IEEE, 2011. p. 43-46.

[12] YANG, Hui; BUKKAPATNAM, Satish TS; KOMANDURI, Ranga. Spatiotemporal representation of cardiac vectorcardiogram (VCG) signals. Biomedical engineering online, v. 11, n. 1, p. 16, 2012.

[13] REGIS, Carlos DM et al. Objective and subjective evaluation of spatially transcoded videos for mobile receivers. 2010.

[14] HORE, Alain; ZIOU, Djemel. Image quality metrics: PSNR vs. SSIM. In: 2010 20th International Conference on Pattern Recognition. IEEE, 2010. p. 2366-2369.

[15] LIGANG, Zhou Wang et al. Video quality assessment using structural distortion measurement. In: in Proc. IEEE Int. Conf. Image Proc. 2002.

[16] REGIS, Carlos Danilo de Miranda. et al. Design of objective video quality metrics using spatial and temporal informations. IEEE Latin America Transactions, v. 13, n. 3, p. 790-795, 2015.

[17] OLIVEIRA, Jean Felipe F. De; REGIS, Carlos Danilo M.; DE ALENCAR, Marcelo Sampaio. Performance Evaluation of the PWSSIM Metric for HEVC and H. 264. Procedia Computer Science, v. 65, p. 115-124, 2015.

[18] CORTEZ, Daniel et al. Visual transform applications for estimating the spatial QRS–T angle from the conventional 12-lead ECG: Kors is still most Frank. Journal of electrocardiology, v. 47, n. 1, p. 12-19, 2014.

Table 1. Clusters of patients.

Diagnosis	Groups	Infarcted Myocardial Wall	Set of signals
Control Group	Group I	Healthy	77
Myocardial Acute Infarction	Group II.a	Anterior	74
	Group II.b	Posterior	25
	Group II.c	Inferior	38
	Group III	Multiarterial	80

Table 2 - Coefficient matrices used to obtain the VCG from the 12-lead ECG.

Method	VCG axis	I	II	III	aVR	aVL	aVF	V1	V2	V3	V4	V5	V6
Kors Linear Regression	X	0.380	-0.070	0.000	0.000	0.000	0.000	-0.130	0.050	-0.010	0.140	0.060	0.540
	Y	-0.070	0.930	0.000	0.000	0.000	0.000	0.060	-0.020	-0.050	0.060	-0.170	0.130
	Z	0.110	-0.230	0.000	0.000	0.000	0.000	-0.430	-0.060	-0.140	-0.200	-0.110	0.310
Kors Quasi-Orthogonal	X	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
	Y	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Z	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.500	0.000	0.000	0.000	0.000
Inverse Dower	X	0.632	0.235	-0.397	-0.434	0.515	-0.081	-0.515	0.044	0.882	1.212	1.125	0.831
	Y	-0.235	1.066	1.301	-0.415	-0.768	1.184	0.157	0.164	0.098	0.127	0.127	0.076
	Z	0.059	-0.132	-0.191	0.037	0.125	-0.162	-0.917	-0.139	-1.277	-0.601	-0.086	0.230

Table 3 - Results for the group of healthy subjects

GROUP I							
Methods		**PSNR [dB]**		**SSIM**		**PW-SSIM**	
		MEAN	**SD**	**MEAN**	**SD**	**MEAN**	**SD**
Frank X Dower IM	**XY**	17.7780	0.7232	0.8957	0.0148	0.8938	0.1359
	XZ	17.8739	0.5726	0.8936	0.0104	0.9002	0.1259
	Y Z	17.6448	0.7035	0.8913	0.0134	**0.9242**	**0.0756**
Frank X Kors QO	**XY**	**18.0062**	**0.6884**	**0.9009**	**0.0130**	**0.9485**	**0.0599**
	XZ	17.8802	0.6263	0.8918	0.0108	**0.9287**	**0.0696**
	YZ	17.7674	0.7213	0.8921	0.0138	0.9170	0.0854
Frank X Kors LR	**XY**	**18.1370**	**1.1790**	**0.9050**	**0.0250**	0.9346	0.1054
	XZ	**17.9680**	**0.9210**	**0.8990**	**0.0170**	0.9147	0.0952
	YZ	17.7570	1.1730	0.8930	0.0250	0.9065	0.0874

Table 4 - Results for the group of subjects with anterior wall infarction.

GROUP II.a							
Methods		**PSNR [dB]**		**SSIM**		**PW-SSIM**	
		MEAN	**SD**	**MEAN**	**SD**	**MEAN**	**SD**
Frank X Dower IM	**XY**	16.8113	0.9290	0.8750	0.0204	0.8767	0.1348
	XZ	17.1137	0.9028	**0.8799**	**0.0188**	0.8668	0.1343
	YZ	16.8475	1.0051	0.8743	0.0248	0.8612	0.1383
Frank X Kors QO	**XY**	**17.3154**	**0.9103**	**0.8889**	**0.0166**	**0.9683**	**0.0788**
	XZ	**17.1867**	**0.9026**	0.8795	0.0192	0.8746	0.1183
	YZ	**16.9565**	**0.9229**	**0.8756**	**0.0211**	0.8771	0.1206
Frank X Kors LR	**XY**	17.0350	1.0260	0.8800	0.0270	0.9286	0.1329
	XZ	17.0740	1.0820	0.8770	0.0280	**0.8780**	**0.1069**
	YZ	16.7170	0.9440	0.8700	0.0260	**0.8981**	**0.0934**

Table 5 - Results for the group of subjects with posterior wall infarction.

GROUP II.b							
Methods		PSNR [dB]		SSIM		PW-SSIM	
		MEAN	SD	MEAN	SD	MEAN	SD
Frank X Dower IM	XY	17.3133	0.7988	0.8865	0.0191	0.9319	0.0715
	XZ	**17.7180**	0.8249	**0.8925**	0.0175	**0.9340**	0.0736
	YZ	**16.9007**	0.7530	**0.8769**	0.0180	0.8403	0.2041
Frank X Kors QO	XY	17.2169	0.8654	0.8837	0.0216	**0.9440**	0.0754
	XZ	17.3416	0.7498	0.8826	0.0174	0.8890	0.1048
	YZ	16.7135	0.7237	0.8730	0.0154	**0.8706**	0.1159
Frank X Kors LR	XY	**17.4960**	1.1280	**0.8920**	0.0280	0.9145	0.0847
	XZ	17.6090	0.7850	0.8920	0.0210	0.9147	0.0943
	YZ	16.6640	0.8400	0.8720	0.0230	0.8588	0.1322

Table 6 - Results for the group of subjects with Inferior wall infarction.

GROUP II.c							
Methods		**PSNR [dB]**		**SSIM**		**PW-SSIM**	
		MEAN	**SD**	**MEAN**	**SD**	**MEAN**	**SD**
Frank X Dower IM	**XY**	17.2883	0.7710	0.8862	0.0133	0.8927	0.1130
	XZ	**17.7502**	0.8265	**0.8941**	0.0169	**0.9346**	0.1156
	YZ	17.1142	0.8048	0.8828	0.0140	**0.8654**	0.1333
Frank X Kors QO	**XY**	**17.4404**	0.8914	**0.8916**	0.0166	**0.9523**	0.0997
	XZ	17.4613	0.7966	0.8850	0.0153	0.8446	0.1205
	YZ	**17.1629**	0.8328	**0.8838**	0.0140	0.8140	0.1406
Frank X Kors LR	**XY**	17.1280	0.9580	0.8830	0.0240	0.9124	0.1034
	XZ	17.3030	1.1500	0.8830	0.0270	0.8671	0.1261
	YZ	16.8710	0.9790	0.8760	0.0270	0.8030	0.1940

Table 7 - Results for the group of subjects with multiarterial infarction.

GROUP III							
Methods		**PSNR [dB]**		**SSIM**		**PW-SSIM**	
		MEAN	**SD**	**MEAN**	**SD**	**MEAN**	**SD**
Frank X Dower IM	**XY**	16.6079	1.0888	0.8703	0.0257	0.8675	0.1283
	XZ	17.1172	1.0922	**0.8812**	0.0207	0.8871	0.1378
	YZ	16.5112	0.9656	**0.8694**	0.0220	0.7996	0.1791
Frank X Kors QO	**XY**	**16.9281**	1.0965	**0.8793**	0.0228	**0.9350**	0.1030
	XZ	**17.1497**	1.0026	0.8802	0.0203	**0.8906**	0.1007
	YZ	**16.5596**	1.0200	0.8687	0.0234	**0.8638**	0.1473
Frank X Kors LR	**XY**	16.5570	1.3600	0.8670	0.0370	0.8902	0.1306
	XZ	16.8950	1.1800	0.8770	0.0280	0.8722	0.1121
	YZ	16.1740	1.1530	0.8580	0.0300	0.8588	0.1341

Figure 1. Flowchart of the project stages.

Figure 2. Vectorcardiogram obtaining methods.

Figure 3. Frank and Kors linear regression VCG for the XZ plane.

Figure 4. Values of the PSNR and SSIM, respectively, for each group and regression method.

Figure 5. Values of the PW-SSIM for each group and regression method.

Author Statement

Ittalo dos Santos Silva: Conceptualization, Methodology, Software **José Raimundo Barbosa**: Software, Data curation, Writing- Original draft preparation, Writing - Review & Editing . **Rafael Duarte de Sousa**: Writing- Original draft preparation, Writing - Review & Editing . **Renato de Aguiar Hortegal***:* Supervision.**: Carlos Danilo Miranda Regis**: Formal analysis, Supervision.

Highlights

- A comparison between vectorcardiography curves obtained by Frank's and alternative ones method from the same exam using the digital signal processing metrics PSNR, SSIM and PW-SSIM.
- The signals were obtained from the Physikalisch-Technische Bundesanstalt Diagnostic ECG Database. The vectorcardiography curves were obtained from Frank's leads and from the 12-lead ECG. The alternative methods were the Kors Quasi-Orthogonal method, Dower's Inverse Matrix method and Kors Linear Regression Method.
- The comparison showed that the alternative methods have high similarity with Frank's Method when the subjects are healthy. Pathological subjects had signals with higher variability of metric values for each regression method.
- The PW-SSIM had higher variance and its values could indicate which planes are most affected by infarction.

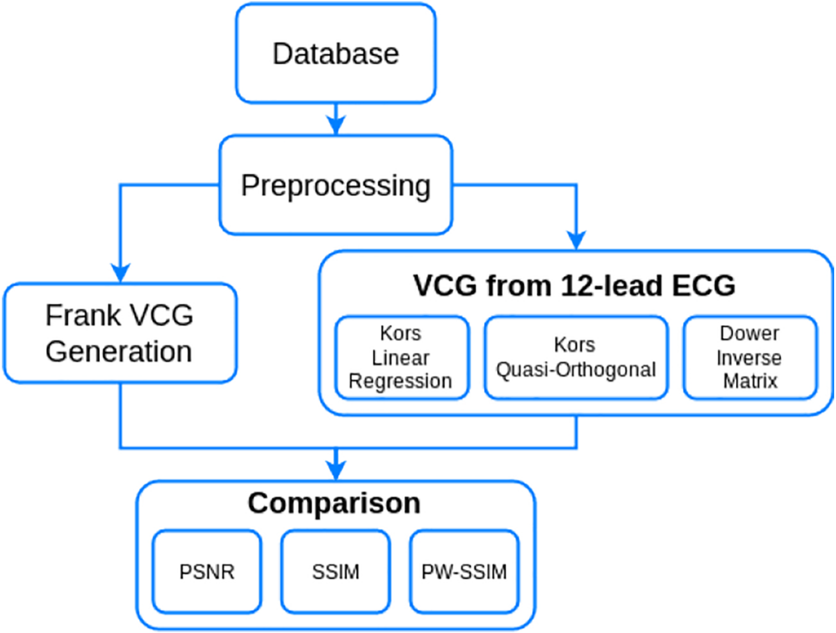

Database
Preprocessing
Frank VCG Generation
VCG from 12-lead ECG
Kors Linear Regression
Kors Quasi-Orthogonal
Dower Inverse Matrix
Comparison
PSNR
SSIM
PW-SSIM

Figure 1

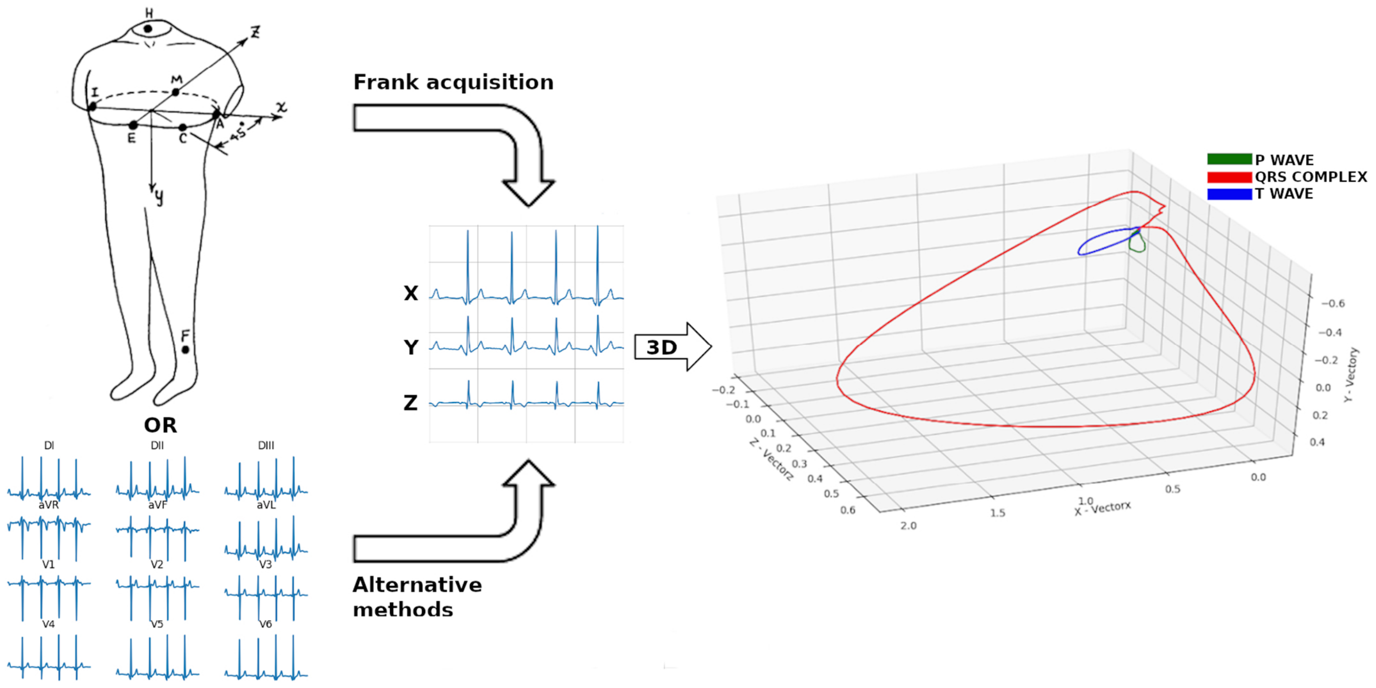

H
Z
M
I
X
A
E
C
45°
y
F
OR
DI
DII
DIII
aVR
aVF
aVL
V1
V2
V3
V4
V5
V6
Frank acquisition
Alternative methods
X
Y
Z
3D
P WAVE
QRS COMPLEX
T WAVE
Z - Vectorz
X - Vectorx
Y - Vectory

Figure 2

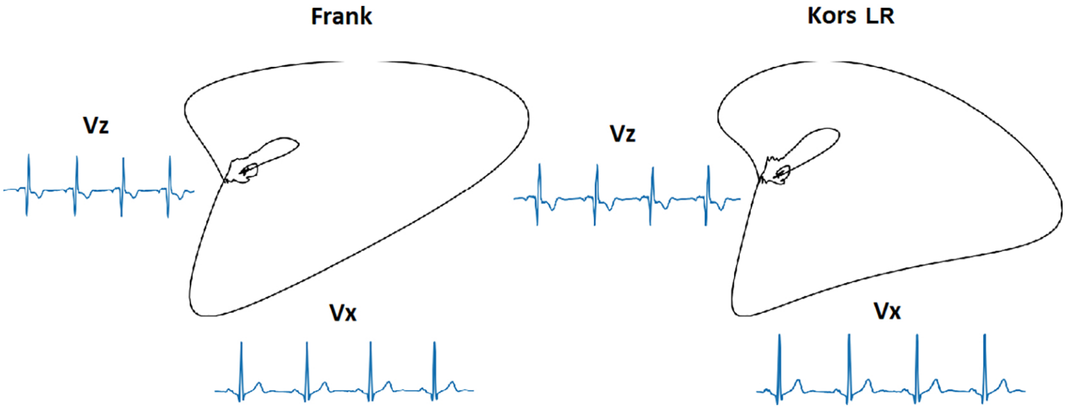


Figure 3

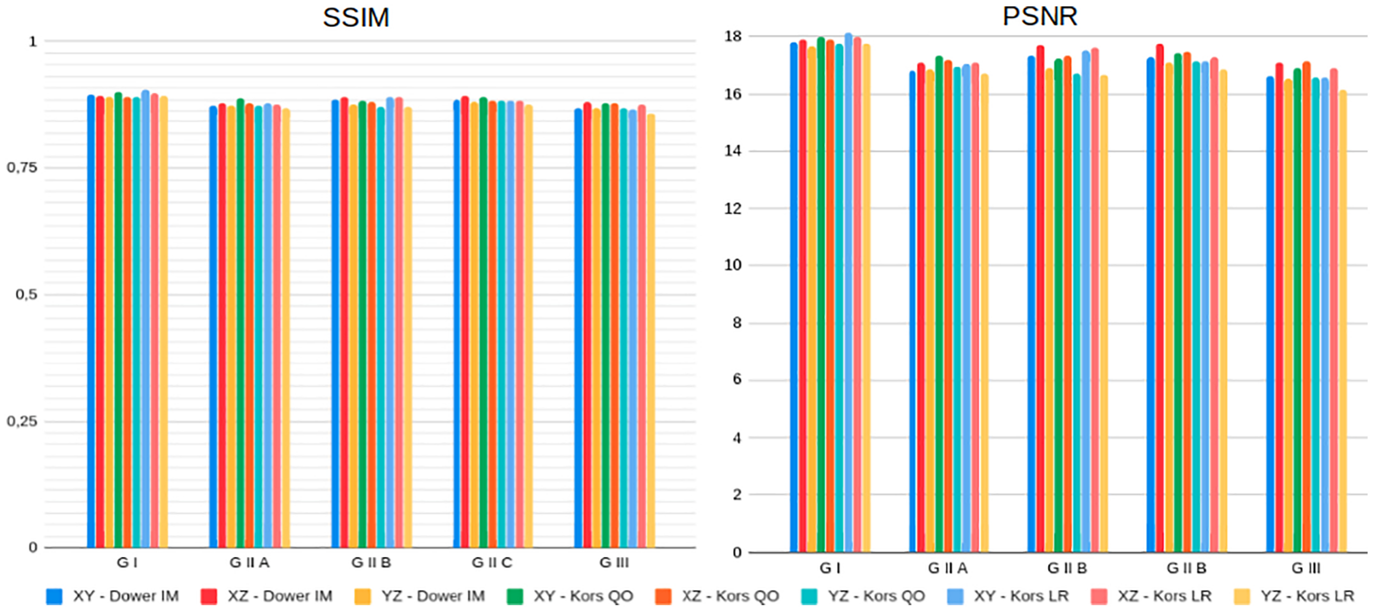

SSIM
1
0,75
0,5
0,25
0
G I
G II A
G II B
G II C
G III
PSNR
18
16
14
12
10
8
6
4
2
0
G I
G II A
G II B
G II B
G III
XY - Dower IM
XZ - Dower IM
YZ - Dower IM
XY - Kors QO
XZ - Kors QO
YZ - Kors QO
XY - Kors LR
XZ - Kors LR
YZ - Kors LR

Figure 4

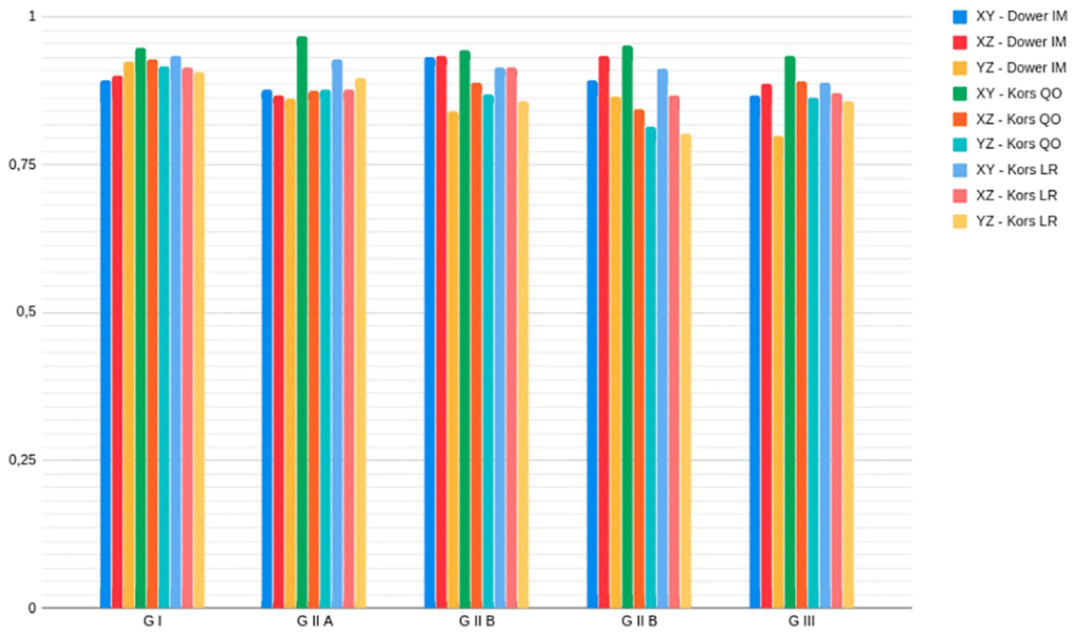

1
0,75
0,5
0,25
0
G I
G II A
G II B
G II B
G III
XY - Dower IM
XZ - Dower IM
YZ - Dower IM
XY - Kors QO
XZ - Kors QO
YZ - Kors QO
XY - Kors LR
XZ - Kors LR
YZ - Kors LR

Figure 5