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Frank Vectorcardiographic system from Standard 12 lead ECG: An effort to enhance cardiovascular diagnosis

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Background— Vectorcardiogram (VCG) has been repeatedly found useful for clinical investigations. It may not substitute but complement Standard 12-Lead (S12) ECG. There was tremendous research between 1950s to mid-1980s on VCG in general and Frank's System in particular, however, in last three decades it has been dropped as a routine cardiac test. The major reasons being unconventional electrode placements which required training of the physicians, greater number of electrodes involved when used to supplement S12 system and additional hardware complexity involved, at least in the early days. Although it lost the interest of cardiologists, the engineering community has adopted the VCG as a tool for interdisciplinary research. We envisage that, if accurate Frank's VCG system is made available avoiding the aforementioned limitations, VCG will complement S12 system in diagnosis of cardiovascular diseases (CVD).

Methods and Results— In this paper, we propose a methodology to construct Frank VCG from S12 system using Principal Component Analysis (PCA). We have compared our work with state-of-the-art Inverse Dower Transform (IDT) and Kors Transform (KT). Mean R^2 statistics and correlation coefficient values obtained for CSE multilead database (CSEDB) and PhysioNet's PTBDB using proposed method were (73.7%, 0.869), for IDT (57.6%, 0.788) and for KT (56.2%, 0.781). From remote healthcare perspective, a reduced 2-3 lead system is desired and Frank lead system seems to be promising as shown by previous works. However, cardiologists are accustomed to S12 system due to its widespread usage and derived Frank lead system might not be sufficient. Hence, to bridge the gap, we have presented the results of personalized reconstruction of S12 system from derived VCG, obtained using proposed PCA-based method and compared it with results obtained when originally measured Frank leads were used.

Conclusions— The proposed methodology, without any modification in the current acquisition system, can be used to obtain Frank VCG from S12 system to complement it in CVD diagnosis. Omnipresent computerized machines can readily apply the proposed methodology and thus, can find widespread clinical application.

Key Words: ECG, VCG, Standard 12-Lead system, Frank System, Principal Component Analysis (PCA), Inverse Dower Transform (IDT). Kors Transform (KT)

INTRODUCTION

Vectorcardiography (VCG) was first introduced in 1920[1] to assist the diagnosis of cardiovascular diseases. VCG diagnostics intend to offer a graphical tool for better instantaneous representation of the cardiac electric activation at each time. In addition to a 3D display, it computes 3D variables which can be used by diagnostic algorithms. Phase information is one such variable which cannot be obtained from ECG diagnostics, it is used to compare the maximal ECG amplitude in an ECG lead with the maximal QRS vector. Since, VCG leads are orthonormal they compensate for the irregular leads in Standard 12-Lead (S12) ECG.

Numerous investigations have been reported using Frank VCG (FV) system[2], the clinical standard for acquisition[*] of VCG, presenting the diagnostic performance and its comparison with S12 system for various cardiovascular diseases viz. left ventricular overload, myocardial infarction, aortic stenosis, left/right ventricular hypertrophy, ischemia etc[3-31]. However, due to the following limitations vectorcardiogram was eventually removed from routine cardiac tests[27]:

1. Different acquisition system was required with added hardware and complexity when both VCG and standard 12-lead systems were acquired together[31].
2. Frank's system requires placement of electrodes on the back and on the neck which is uncomfortable for supine patients[2]. To accommodate large number of electrodes for a combined S12 and FV system in routine tests was difficult for both patients and care-givers[31].
3. Physicians were needed to acquire skillset for accurate placement of electrodes and VCG analysis[31].

Due to the aforementioned limitations VCG was dropped from the routine tests, thereby making it unavailable for diagnosis and research. This investigation aims to address this problem as VCG offers several advantages as have been outlined previously and can be used to complement S12 system. Previously, the Kors Transform[3] (KT) and the inverse Dower matrix[4,6] (IDT) have been proposed to address the unavailability of VCG, however, they encounter several limitations. Inverse Dower matrix (and Dower matrix) is based on the Frank torso model, which does not account for the anatomical variations among different subjects. Moreover, the Frank torso model lacks conduction inhomogeneity (no lungs) which makes it less realistic. On the other hand, in the Kors matrix that is essentially a statistical compromise, results are optimized for a group. Some patients will fit well in this approach, others not. There is, hence, place for approaches different from the inverse Dower and Kors matrices; especially an individualized approach might be attractive. Such an approach is, indeed, the one we propose in this paper where we introduce a methodology to construct Frank's leads from Standard 12-Lead system using principal component analysis (PCA) by exploiting the vector space projections of leads of S12 system on the orthogonal planes i.e. sagittal, frontal and transverse. The proposed method allays the requirement of additional hardware (including extra electrodes) and complexity accompanied with the acquisition or capturing of FV lead System. The proposed methodology has been compared with state-of-the-art Kors Transform[3] and Inverse Dower Transform[4,6], which are generally employed in clinical usage to obtain VCG when required.

[*] Throughout this paper, the word acquisition implies capturing or recording of data using the required hardware e.g. general ECG machines used for the acquisition of Standard 12-Lead system in hospitals.

BACKGROUND

Here, we present a brief review on the importance of VCG, derived using Frank's System, from medical and engineering perspective. The following subsections highlight this paper attempts to address the requirements and/or limitations posed by aforementioned perspectives. The relevance of FV system alongside S12 system to enhance the diagnostic efficiency for cardiovascular diseases has also been highlighted.

Since, the foundation of VCG was laid in 1920[1], VCG is still in existence, though, may not be in the form which cardiologists had earlier expected. In early 1950s several uncorrected and corrected lead systems were proposed viz. Simonson, Frank, McFee and Johnston[2,5,7] and extensive experiments were performed to qualify one system over the other[5,7]. Frank's system[2], however, was finally adopted as standard system for vectorcardiography by late 1960 due to several advantages: simplicity of application, reasonably accurate representation of heart dipole and adequate number of electrodes to better approximate the fixed dipole assumption of the heart[5,14].

A. CLINICAL PERSPECTIVE

FV system since its adoption has been used to classify normal and abnormal patients[8], younger and older normal patients[12], patients with myocardial infarction and its variants[16,23,29,30,43,46,52], left ventricular overload and left/right ventricular hypertrophy[9,14,15], aortic stenosis[11,22] etc. Multivariate analysis have been applied to both S12 ECG and FV systems to present a comparison on their diagnostic efficiency. In most of the cases, it was found that VCG performed, if not better, at the least as good as ECG[11,15,18,21,22,25,27,28]. Some authors have suggested the use of a hybrid 15-lead system which includes both S12 and FV for better diagnosis[18,21,25,28] as it is more likely to produce enhanced diagnostic confirmatory signs. A recent paper compares the QRS-T angles of golden standard Frank VCG with constructed FV system using IDT and KT[53]. The persisting interest in VCG from the medical community shows the diagnostic capabilities of VCG.

With the growing number of cardiovascular diseases' patients across the globe, remote healthcare[55] has been proposed as a next generation solution to diagnosis and monitoring of chronic cardiovascular diseases. Due to technological constraints of limited bandwidth, storage and transmission time encountered, a reduced 2-3 lead/channel system is desired in such scenarios. We have proposed several lead reconstruction methodologies[50,51,54] to reconstruct S12 system from Reduced 3-Lead (R3L) systems, thereby allaying the technological constraints along with availability of standard 12-leads to the cardiologists. FV system was found to outperform other R3L systems for reconstructing the S12 leads. However, usage of Frank leads in remote healthcare is limited due to its availability, which involves the additional burden of accompanying extra electrodes and hardware for its acquisition.

B. ENGINEERING PERSPECTIVE

The fixed current dipole model of the heart lies at the center of heart modeling. It is the simplest model to explain the electrical properties of heart. Along with the persisting interests of cardiologists in FV system, interdisciplinary research in collaboration with engineers has led to numerous investigations on reconstruction, acquisition and analysis of FV lead system. Several works have been communicated proposing automated VCG analysis and interpretation algorithms using various mathematical tools[33-35,39,41,43-45,47]. The acquisition of FV lead system involves 8 electrodes and its simultaneous acquisition along with S12 system will cause greater discomfort to the patients due to increased number of electrodes. To address this constraint, several lead reconstruction methodologies were proposed i.e. universal transformation matrices[1-3], population based transformation matrices[48,49] and personalized transformation matrices[50,51,54]. Population-based and personalized transformation matrices are superior to universal matrices, however, they require simultaneous acquisition of both FV and S12 lead systems. On the other hand, IDT has been derived from the data obtained from homogeneous torso model which Frank used to propose VCG system, thus, it is not accurate due to various assumptions such as homogeneity and fixed body characteristics. KT was population specific transformation matrix obtained from CSEDB using linear regression method and was later used in several investigation as universal transformation matrix. Population specific transformation coefficients depend upon the database used and have relatively lower accuracy compared to personalized or patient tailored coefficients. It depends on number of subjects and their disorders. The aforementioned limitations keep the fundamental quest of obtaining accurate FV system from S12 open, yet to be addressed.

MATERIAL and METHOD

Fig. 1 shows the summary of the methodology followed in this investigation. First the databases are denoised using the preprocessing module followed by PCA module for the construction of FV from S12 system. IDT and KT were also used to reconstruct Frank's leads. All the three sets of derived Frank leads were then compared with actually recorded Frank leads. Finally, the S12 leads was reconstructed from the derived[†] FV leads, obtained using the proposed PCA-based methodology and were compared with the originally measured S12 leads. The personalized reconstruction of S12 system from derived FV system further includes a module for generation of transformation coefficient. We will discuss all the aforementioned modules in detail in the following subsections:

I. MATERIAL

PhysioNet's PTB database (PTBDB)[56,57] and dataset-3 and dataset-4 of the multilead CSE database[58] (CSEDB) were used in this investigation. All the 549 records of 290 patients of PTBDB and 250 original multilead recordings of CSEDB were used. Both are 15-lead databases which include standard 12-leads and Frank's leads. The sampling frequency and recording length for PTBDB were 1 kHz and not more than 115 sec and for CSEDB, 500Hz and 10 sec. PTBDB consists of 52 healthy control subjects and 238 unhealthy subjects, additional investigation has been carried out for the two groups separately. Unhealthy

[†] The words derived and constructed have been used synonymously in this paper to refer to the X, Y and Z leads obtained using our proposed PCA-based methodology.

subjects include a wide range of cardiovascular diseases viz. myocardial infarction, cardiomyopathy, bundle branch block, Myocarditis, hypertrophy etc. For CSEDB all the patients have been considered as a single group because of unavailability of diagnostic results of individual patients. The patients used have been gross classified and we have avoided going into details of individual abnormalities, since, the paper intends to propose a methodology.

II. PREPROCESSING

Preprocessing module includes baseline wandering removal and denoising. Discrete wavelet transform with symmlet 10 wavelet was used for baseline wandering removal and translational invariant wavelet transform with symmlet 8 wavelet was used for denoising. The procedure has been adopted from our previously published works[50,51,54], hence, its detailed discussion has been omitted over here. Since, the sampling frequency of PTBDB (1 kHz) and CSEDB (500 Hz) are different, the level of decomposition has to be determined while removal of baseline wandering. After wavelet based denoising the length of recording used were the nearest dyadic lengths (2^n) i.e. 10s (5000 samples) recordings of CSEDB were reduced to 4096 samples after denoising. Similarly for different lengths of recording available in PTBDB, 38s (38000 samples) recordings were reduced to 32768 samples and 115s (115000 samples) recordings were reduced to 98304 samples. All the samples of each patients after denoising were used in this paper. After preprocessing, all recordings were mean centered and normalized.

III. PROPOSED VCG CONSTRUCTION METHODOLOGY USING PCA

Dimensionality reduction is the main objective of PCA[59]. It obtains the set of points which is the best representation of dataset, known as principal component. The 1st principal component has the maximum variance, hence maximum information, and it decreases with 2nd, 3rd and so on. Fig. 2 shows the working principal of PCA. For a 2-D case, PCA finds a lower 1-D linear vector on which when the dataset is projected produces lowest mean square of the perpendicular distances from the points to the vector. This linear vector is known as a principal component. For higher dimensions, a lower dimensional plane or hyperplane represented by spanning vectors (principal components) is searched. When PCA was applied on a subset (I, V_5, V_6) of S12 system, the first principal component obtained was found to have 98.69 % resemblance with the originally measured X lead of FV system, as shown on the right hand side of Fig. 2.

The theoretical background for the resemblance observed between 1st principal component and X lead in Fig. 1 can be explained using Heart-Vector Projection theory[60]. This theory states that heart can be approximated as a single current dipole vector ($\vec{H}$) fixed in space. Orientation and magnitude of the heart vector varies during the cardiac cycle and its projection on the lead vector ($\vec{L}$) produces the potential observed when electrodes are placed on the body (1). Unipolar lead vectors are assumed to originate from the zero-potential region in heart (also serves as origin) and terminates at the point of location of the electrode.

$$V = \vec{H}.\vec{L} = aX + bY + cZ \quad (1)$$

Where $\vec{H} = X\hat{\imath} + Y\hat{\jmath} + Z\hat{k}$ and $\vec{L} = a\hat{\imath} + b\hat{\jmath} + c\hat{k}$. Though Heart-Vector Projection theory is the simplest model of heart, the underlined assumptions of fixed dipole provides incomplete information on the condition of heart. However, for all practical purposes the dipole model is used, owing to its simplicity and significant diagnostic accuracy.

From (1), it can be seen that if an appropriate lead vector ($\vec{L}$) can be obtained such that it is parallel to $\hat{\imath}$ i.e. x-axis, then the potential measured at that location would yield the *X* component of $\vec{H}$. This is the fundamental idea behind FV system[6]. Taking Heart-Vector Projection theory as a background, we propose the following hypothesis:

Since, all observed body surface potentials result from projection of the heart vector ($\vec{H}$) on the lead vector ($\vec{L}$), it should be possible to extract back the heart vector components from an adequate set of body surface potentials.

In other words, the information of $\vec{H}$ is hidden in the signals acquired by the electrodes placed on the body. In this paper, standard leads of S12 system have been used as a set of body surface potentials. We propose that by applying PCA on 3-lead subsets of S12 system to reduce redundancy and extract the most significant information, the first principal component obtained resembles to VCG lead which has dominant contribution to the subset. Subset of leads *I*, V_5 and V_6 have been selected for construction of *X*; *II*, *III* and aVF for Y and V_1, V_2 and V_3 for *Z*. The following two arguments justify the selection of aforementioned subsets:

A. Fig. 3-1 presents the electrode placement positions and the coordinate axes used by Frank in his VCG system. Fig. 3-2 presents lead vector projections on the three perpendicular planes i.e. frontal, horizontal and sagittal. Please note that y' and z' are negative y and z-axes. Taking note of the directions of leads *I*, V_5 and V_6 in Fig. 3-2, we can find that its orientation is towards *X* component of $\vec{H}$. It can be argued that, in view of lead *I*'s direction, it should independently yield the *X* component, however, it should be noted that the orientation of lead *I* might not be perfectly along $\hat{\imath}$ in the image surface proposed by Frank[60]. Hence, three leads were chosen so as to maximize the information content of the principal component upon PCA, assuming that image surface orientations of the subsets lie towards the *X* component, if not perfectly aligned with it. Using similar argument, a subset of leads *II*, *III* and *aVF* was used for Y^{th} component of $\vec{H}$ and subset comprising V_1, V_2 and V_3 was used for the Z^{th} component. Precordial leads are unipolar and hence, there direction is also the direction of respective lead vectors. Thus, using Heart-Vector projection theory, the potentials obtained at those leads are projection of $\vec{H}$ on them. Similar, arguments can be drawn for bipolar leads. Thus, it can be safely assumed that the corresponding heart components are the major contributors of the potential observed at the aforementioned respective subsets. It should be noted that lead aVF has been used along with II and III, which is dependent and redundant. However, the orientation of aVF is along the Y-axis in the frontal plane (Fig. 3-2) and it was found that inclusion of aVF yielded superior results compared to when otherwise.

B. Transformation of FV system to S12 system were obtained using personalized transformation[51] and mean coefficients were calculated (please see appendix) for both PTBDB and CSEDB. The transformation coefficients represent the relative contribution of various Frank leads to S12 leads. Table 1 and 2 present the relative contributions of heart vector components in S12 leads for PTBDB and CSEDB respectively. Higher value represents greater contribution of one component over the others. From both Table 1 & 2, we can see that *I*, V_5 and V_6 have dominant contribution of *X* compared to *Y* and *Z* components. Leads *II*, *III* and *aVF*, clearly presents dominant contribution of *Y* compared to *X* and *Z*. The balanced and dominant contribution of *Z* from Tables 1 & 2 is not readily visible however, leads V_1, V_2 and V_3 can be found to lead among the rest.

IV. PERSONALIZED TRANSFORMATION COEFFICIENT GENERATION

Generalized form of (1) can be written as (2):

$$V = a_i l_1 + b_i l_2 + c_i l_3 \qquad (2)$$

Where l_1, l_2 and l_3 are any three leads and a_i, b_i and c_i are corresponding lead vector components for *V*. If potentials on either side of (2) are known then lead vector components can be obtained using least square fit method (3).

$$\begin{bmatrix} a_i \\ b_i \\ c_i \end{bmatrix} = \begin{bmatrix} \sum l_1^2 & \sum l_1.l_2 & \sum l_1.l_3 \\ \sum l_1.l_2 & \sum l_2^2 & \sum l_2.l_3 \\ \sum l_1.l_3 & \sum l_2.l_3 & \sum l_3^2 \end{bmatrix}^{-1} \times \begin{bmatrix} \sum V.l_1 \\ \sum V.l_2 \\ \sum V.l_3 \end{bmatrix} \qquad (3)$$

Lead vector components or coefficients obtained using (3) are known as transformation coefficients. Eq. (3) employed on individual patient results in patient-specific or personalized transformation (PT) coefficients. Similarly, when employed on set of recording it leads to population-based coefficients. Previously, it has been proved that PT outperforms other transformation methodologies[50,51,54], hence, has been employed in the present investigation. For PTBDB and CSEDB, first 5000 and 500 samples were taken to compute (3) respectively. The complete work was carried out on MATLAB (Version 7.10.0.499 R2010a)

V. EVALUATION METRICS

R^2 statistics (4) and correlation coefficient (5). R^2 statistics[49] measures the degree of association between two signals. Perfect matching would be indicated by 100%. However, it should be noted that R^2 may result in negative values if the signals do not match or are out of phase. Correlation coefficient estimates the similarity between two signals. The metrics have been used to compare constructed FV system using the proposed PCA-based method with the originally measured FV leads. Similarly, Frank leads reconstructed using IDT and KT have also been independently compared with originally measured leads. Thereupon, the metrics have been used to evaluate the accuracy with which S12 system is reconstructed from derived Frank leads, derived using our proposed PCA-based method, with measured S12 leads.

$$R^2 = \left\{1 - \frac{\Sigma[D(k)-O(k)]^2}{\Sigma[O(k)]^2}\right\} \times 100 \qquad (4^{\ddagger})$$

$$r_x = \left\{\frac{\Sigma O(k) \times D(k)}{(\Sigma O^2(k) \times D^2(k))^{1/2}}\right\} \qquad (5)$$

RESULTS

The derived Frank leads, obtained using three different methodology viz. the proposed PCA-based method, IDT and KT have been compared independently with the originally recorded Frank lead using the evaluation metrics in Table 3. It shows the number of patients (in %) in various ranges of mean R^2 values. Mean was taken over derived X, Y and Z leads of FV system and all the patients of PTBDB and CSEDB were included. All the transformations have performed relatively well for CSEDB compared to PTBDB. For PTBDB, PCA-based has significantly outperformed IDT and KT transformations. However, for CSEDB, KT outperforms the PCA-based method followed by IDT. Superior results obtained for KT[3] on CSEDB can be explained upon considering that it was derived using population based linear regression method from CSE database itself, which has since been used as the universal transformation matrix. However, KT fails to replicate its performance in PTBDB. It should be noted that KT produces a positive R^2 values only in 56.47% of patients for PTBDB, for all other patients it critically fails. The proposed PCA-based method is personalized compared to database based Kors Transform. IDT's performance fluctuates with respect to KT, for positive R^2 values IDT outperforms KT for PTBDB, however, for R^2 values greater than 50% KT has outperformed IDT. IDT is based on the assumption of homogeneity and fixed body characteristics, however, KT has been obtained from real patients, hence, includes the effects due to heterogeneity and other body characteristics i.e. body fat distribution, size and shape of the body.

Table 4 presents a comparison in performance of proposed PCA-based method on the first recordings of patients in PTBDB, which excluded patients with pace makers and other therapies, and the remaining recordings. First recordings were further subdivided into healthy control and unhealthy subjects. A remarkable difference of 5.73% (R^2) in performance for healthy subjects can be seen compared to unhealthy subjects and 29.09% (R^2) for first recording compared to rest. Even if electrode placement error is considered, it does not explain the considerable difference in reconstruction result, since, 290 first recordings and 259 further records were considered. Condition of heart can severely affect the reconstruction process. It was also pointed out in our previous works on lead reconstruction[50,51,54]. This comparison supports the theoretical basis behind the PCA-based reconstruction methodology.

Table 5 presents the reconstruction results of S12 system from derived FV system. The Frank leads used for reconstruction of S12 system have been synthesized using our proposed PCA-based method. Previously, it has been shown that personalized transformations outperformed state-of-the-art Dower transform[1,51] and Affine transform[49,51], here, in Table 5 we present a comparison between the personalized reconstruction of S12 system from derived FV leads and original FV leads. Derived FV leads outperform original FV leads by 5.24 % and 2.19% for PTBDB and CSEDB respectively.

‡ D – Derived signal; O – Originally measured signal

Fig. 4 shows the comparison between derived (red) and originally measured (blue) FV leads for three different patients in PTBDB. The mean R^2 values of the three patients lie close to mean, median and maximum R^2 values respectively, obtained using PCA-based method. Corresponding reconstruction performances for IDT and KT have also been shown. Fig. 4 A-C presents mean case patient's FV leads (X, Y and Z) reconstruction using PCA-based method, IDT and KT respectively. Similarly, Fig. 4 D-F shows the median case and Fig. G-I shows the maximum case for PCA-based method, IDT and KT respectively.

Fig. 5 presents a similar comparison as mentioned in previous paragraph for mean, median and maximum case patients in CSEDB using PCA-based method and its comparison with IDT and KT. Fig. 5 A-C presents mean case patient, Fig. 5 D-F presents median case and Fig. 5 G-I presents maximum case. Fig. 4 & 5, contains a range of R^2 values (20.94 % to 99.51 %) and presents a relation between R^2 values and its corresponding reconstruction. From the wide variety of evaluation results and consultation with two co-authoring experienced cardiologists, we conclude that the R^2 value of 80 % and above can be assumed to be diagnostically accurate for all practical purposes.

DISCUSSION

Proposed PCA-based personalized method vis-à-vis model-based/statistically determined VCG Synthesis:

In Table 3, particularly in CSEDB, KT has outperformed the proposed PCA-based algorithm for the cases when mean R^2 values are >50%, >80% and >90%, this is because KT is a population based transform matrix which was obtained using data in CSEDB[58]. However, in the case of PTBDB, the proposed methodology has outperformed both IDT and KT, which shows that universal matrix or population based transformation matrix do not guarantee accurate results. The disparity in results obtained from the two databases i.e. PTBDB and CSEDB as observed in Tables 3 and 5 can also be attributed to the following factors: different experimental setups used in acquisition of the databases, noise levels, disease profile, anatomical build of the subjects, accuracy in electrode placements and the acquisition hardware used. The first commercially available ECG machine viz. Marcquette Electronics MAC-I was introduced in 1979[61]. As reported by the CSEDB, the acquisition of ECG was performed in the year 1983-84 and that of PTBDB was performed in 1995. A decade of gap can significantly vary the technology used in manufacturing sensors, ADCs etc., used in the hardware acquisition systems. For example, the resolution reported by CSEDB is 5μV/bit and PTBDB is 0.5μV/bit which can result in greater accuracy with respect to the morphology of ECG signal acquired.

Advantages, limitations and future research scope of the proposed methodology:

Fig. 3 is a simplistic 2-D representation or planar view of various standard leads, however, an accurate representation can be seen in Fig. 6. The fixed lead subsets chosen for the reconstruction of Frank's leads i.e. *X* (*I*, V_5, V_6), *Y* (*II*, *III*, *aVR*) and Z (V_1, V_2, V_3) have been highlighted using green triangles, yellow rectangles and blue ellipsoids respectively. It can be seen that leads V_1, V_2 and V_3 lie in close vicinity of negative Z-axis (Z') in the sagittal plane, hence, the proposed methodology assumes that upon application of PCA on this subset of three leads, the 1st principal component will orient itself along the direction of Z'. Similar assumptions have been made for other subsets i.e. 1st principal component of *II*, *III*, *aVR* and *I*, V_5, V_6 should be along Y and X-axis respectively. However, it should be noted that other possible subsets of leads can also be used since they orient themselves closer to one of the axes, this has been quantitatively discussed in the following paragraph. The orientations of chosen lead subsets play an important factor in determining accuracy of the methodology, in CVD patients the lead strengths and orientation change compared to normal subjects, hence, the resulting 1st principal component upon applying PCA, which gives preference to a specific lead among the 3-lead subset depending on the energy content, will also be affected and might deviate further from the corresponding axis, thus making the proposed methodology sensitive to lead vector directions. Therefore, although personalized approach may be an important advantage of the PCA-based method, but the fact that PCA components have no actual orientation in physical or in image space and that there could be limitations in terms of sensitivity and normalization.

In this paper, we have used fixed lead subsets of S12 system for the reconstruction of Frank's leads i.e. *X* (*I*, V_5, V_6), *Y* (*II*, *III*, *aVR*) and Z (V_1, V_2, V_3) and correspondingly the first principal component has been used, thus standardizing the methodology. However, when all possible 3-lead subset combinations (${}^8C_3$ = 56) of 8 independent leads (I, II, V_1, V_2, V_3, V_5 & V_6) were used and second principal component was also included in evaluation, some three subsets among them could be found to reconstruct Frank leads with better accuracy compared to aforementioned standard subsets. For PTBDB, the mean R^2 values were found to be 90.73 % compared to 71.19 % for lead *X*, 95.34 % compared to 74.54 % for *Y* and 90.66 % compared to 51.6 % which is considerably better than that reported for fixed chosen subsets. For CSEDB, similar trends were observed i.e. 97.06 % compared to 89.94 % for *X*, 89.59 % compared to 78.83 % for *Y* and 94.38 % compared to 76.02 % for Z. In general, those subsets of S12 leads whose lead vector projections are either oriented towards a coordinate axis or perpendicular to it, tend to produce better reconstruction results (see Fig. 3 & 6). However, none of other combinations of lead subsets consistently outperformed the aforementioned standardized lead subsets. This opens the course to future tasks of understanding the reason behind results obtained from different subsets and proposing of a better methodology of extracting highly accurate Frank leads from Standard 12-lead system using various mathematical techniques. The proposed methodology requires the standard 12-leads to be normalized, so that the magnitude of lead vectors are all equal. It is also required that the placement of electrodes is accurate during the acquisition of standard 12-leads so that the deviation of lead vectors from their accurate direction is minimal.

CONCLUSION

Vectorcardiography in general and Frank system in particular, were postulated and realized six decades ago in pre-informatics period devoid of modern computing capabilities and low power low cost electronic devices. The authors, hence, strongly believe that possible advantages of orthogonal leads were not fully explored. Unavailability of hassle-free Frank VCG was among the primary reasons behind dropping it from routine tests. In this paper, we have attempted to address this issue. The following conclusions can be drawn from this investigation:

1. A novel methodology has been proposed to reconstruct Frank Vectorcardiographic leads from Standard 12-Lead system using PCA.
2. The methodology proposed in this paper does not require any extra electrode or hardware.
3. Theoretical background for the methodology has been provided and validity of the theory has been highlighted using results.
4. The result section shows that the proposed methodology has produce superior results in comparison to state-of-the-art Inverse Dower Transform (IDT) and Kors Transform (KA) for two databases PTB and CSE.
5. Personalized lead reconstruction of Standard 12-leads have been performed from derived Frank leads, derived using our proposed methodology. The results outperform previously proposed methodologies.
6. This paper opens course for future research in accurate reconstruction of Frank system from Standard 12-lead system, using linear algebra techniques, allaying the need of simultaneous acquisition of both the lead systems.

We believe that the proposed methodology would likely to promote new thinking and perhaps rejuvenation of concepts and interests in the VCG that were prevalent over a half century ago

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APPENDIX

Mean coefficients for transformation of Frank VCG system to Standard 12-Lead system for PTBDB (C1) and CSEDB (C2). The Tables C1 & C2 have been utilized in methods section (III B).

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LEGENDS

Fig 1 – Summary of the methodology followed in this paper for reconstruction of Frank system from Standard 12-lead system and then using the derived Frank leads (*DX*, *DY* and *DZ*) to reconstruct standard 12-leads using personalized transformation employing least square fit method and Heart- Vector projection theory.

Fig 2 – Effect of PCA on a data set and when applied on 3-lead subset of standard 12-lead system. The subset in the figure includes *I*, V_5 and V_6. The resulting first principal component is shown as a continuous plot in green whose resemblance to originally measured Frank's X lead is 98.69 %.

Fig 3 – (**1**) Electrode placement position in Frank VCG system along with orientation of 3-D coordinate axes[6]. (**2**) The projection of lead vectors of standard 12-lead ECG in three orthogonal planes (taken from http://www.bem.fi/book/15/15.htm (reference 62) and modified). **Y'**- negative y-axis, **Z'**- negative z-axis.

Fig 4 – Comparison between original (in blue) and derived (in red) signals of Frank system when constructed from Standard 12-lead system. A, D and G shows the construction using our proposed PCA-based method for the subjects which had mean, median and maximum R^2 value in **PTBDB**. B, E and H shows reconstruction for Inverse Dower Transform and C, F and I shows reconstruction for Kors Transform for the same subjects.

Fig 5 – Comparison between original (in blue) and derived (in red) signals of Frank system when constructed from Standard 12-lead system. A, D and G shows the construction using our proposed PCA-based method for the subjects which had mean, median and maximum R^2 value in **CSEDB**. B, E and H shows reconstruction for Inverse Dower Transform and C, F and I shows reconstruction for Kors Transform for the same subjects.

Fig 6 – This figure shows an accurate 2-D representation of 3-D view of standard leads along the chosen coordinate system. **Y'** denotes the negative Y-axis, similarly **Z'** denotes negative Z-axis. The blue ellipsoids on V_1, V_2 and V_3 in the sagittal view can found to orient themselves closer to negative Z-axis (**Z'**) compared to other axes. Similarly leads II, III and aVF inside yellow rectangles can be found to orient themselves along the Y-axis and leads I, V5 and V6 in green rectangles orient themselves closer to the X-axis. (The figure has been adopted from http://www.bem.fi/book/ (reference 62) and modified for the usage in this paper).

Table 1 – Fractional content of heart dipole components in S12 leads For PTB database

	x/y	*x/z*	*y/x*	*y/z*	*z/x*	*z/y*
I	**7.338**	**10.06**	0.136	1.370	0.099	0.730
II	0.164	8.155	**6.112**	**49.85**	0.123	0.020
III	0.589	1.296	**1.699**	**2.202**	0.771	0.454
AVR	0.129	0.245	7.767	1.904	4.079	0.525
AVL	0.797	3.560	1.255	4.468	0.281	0.224
AVF	0.355	1.583	**2.821**	**4.465**	0.632	0.224
V_1	0.677	2.079	1.477	3.071	**0.481**	**0.326**
V_2	2.773	3.352	0.361	1.209	**0.298**	**0.827**
V_3	1.239	8.521	0.807	6.876	**0.117**	**0.145**
V_4	0.834	17.23	1.199	20.67	0.058	0.048
V_5	**0.445**	**5.094**	2.254	11.48	0.196	0.087
V_6	**0.996**	**4.884**	1.004	4.905	0.205	0.204

Table 2 – Fractional content of heart dipole components in S12 leads for CSE database

	x/y	*x/z*	*y/x*	*y/z*	*z/x*	*z/y*
I	**7.207**	**13.79**	0.139	1.914	0.072	0.523
II	0.315	2.829	**3.178**	**8.990**	0.354	0.111
III	0.540	2.927	**1.850**	**5.417**	0.342	0.185
aVR	1.141	126.5	0.877	110.9	0.008	0.009
aVL	1.082	7.522	0.924	6.953	0.133	0.144
aVF	0.149	0.833	**6.722**	**5.594**	1.202	0.179
V_1	2.637	0.592	0.379	0.224	**1.691**	**4.458**
V_2	0.295	0.086	3.385	0.290	**11.65**	**3.443**
V_3	3.301	0.574	0.303	0.174	**1.744**	**5.756**
V_4	81.77	1.401	0.012	0.017	0.714	58.36
V_5	**6.204**	**3.472**	0.161	0.560	0.288	1.787
V_6	**3.155**	**14.89**	0.317	4.718	0.067	0.212

Table 3 – Number of subjects (in %) of subjects with various values of reconstruction accuracy of Frank system from Standard 12-lead system for both PTBDB and CSEDB using our proposed methodology (PCA-based), Inverse Dower transform (IDT) and Kors transform (KT).

Mean R^2 values	No. of patients in CSEDB (in %)			No. of patients in PTBDB (in %)		
	PCA-based	IDT	KT	PCA-based	IDT	KT
> 0 %	100 %	98.8 %	99.6 %	97.63 %	73.04 %	56.47 %
> 50 %	90.4 %	94 %	97.2 %	73.95 %	47.91 %	47.18 %
> 80 %	68 %	66.8 %	75.2 %	40.98 %	30.05 %	34.97 %
> 90 %	48.8 %	40 %	55.6 %	19.85 %	11.66 %	19.31 %
Overall mean R^2 value	81.6 %	80.93 %	85.52 %	65.77 %	34.15 %	26.89 %
Overall mean correlation coefficient	0.8289	0.6708	0.6344	0.9080	0.9046	0.9276

Table 4 – Fraction (in %) of subjects in PTBDB with various reconstruction accuracy values for reconstruction of Frank system from Standard 12-lead system for healthy control (HC), unhealthy (UH) and remaining records.

Mean R^2 values	First recording (290 records)		Remaining records (259 records)
	Healthy Control (HC - 52)	Unhealthy (UH - 238)	
> 0 %	100 %	99.2 %	96.14 %
> 50 %	92.31 %	92.44 %	58.69 %
> 80 %	82.69 %	67.65 %	17.76 %
> 90 %	63.46 %	47.06 %	2.703 %
Overall mean R^2 value	86.63 %	80.90 %	52.84 %
Overall mean correlation coefficient	0.933	0.904	0.764

Table 5 – Mean R^2 and correlation coefficient values for the reconstruction of standard 12-lead system from derived Frank leads, derived using PCA-based methodology and its comparison with the reconstruction result using originally measured Frank leads.

Leads	PTBDB				CSEDB			
	Derived Frank leads		Original Frank leads		derived Frank leads		original Frank leads	
	R^2 (%)	Correlation coefficient (r_x)	R^2 (%)	Correlation coefficient (r_x)	R^2 (%)	Correlation coefficient (r_x)	R^2 (%)	Correlation coefficient (r_x)
I	48.85	0.527	46.39	0.494	92.06	0.9646	89.91	0.950
II	97.57	0.987	92.21	0.959	98.36	0.9928	95.29	0.977
V_1	87.54	0.930	92.91	0.961	92.45	0.9609	91.61	0.961
V_2	97.32	0.986	83.87	0.912	97.67	0.9884	87.41	0.954
V_3	96.56	0.983	85.73	0.920	96.28	0.9840	92.86	0.967
V_4	94.82	0.972	88.34	0.935	93.49	0.9676	95.41	0.977
V_5	97.25	0.986	90.42	0.947	97.15	0.9871	97.46	0.988
V_6	97.31	0.987	95.39	0.975	97.54	0.9912	97.46	0.988
Mean	89.65	0.9198	84.41	0.8878	95.62	0.9795	93.43	0.970

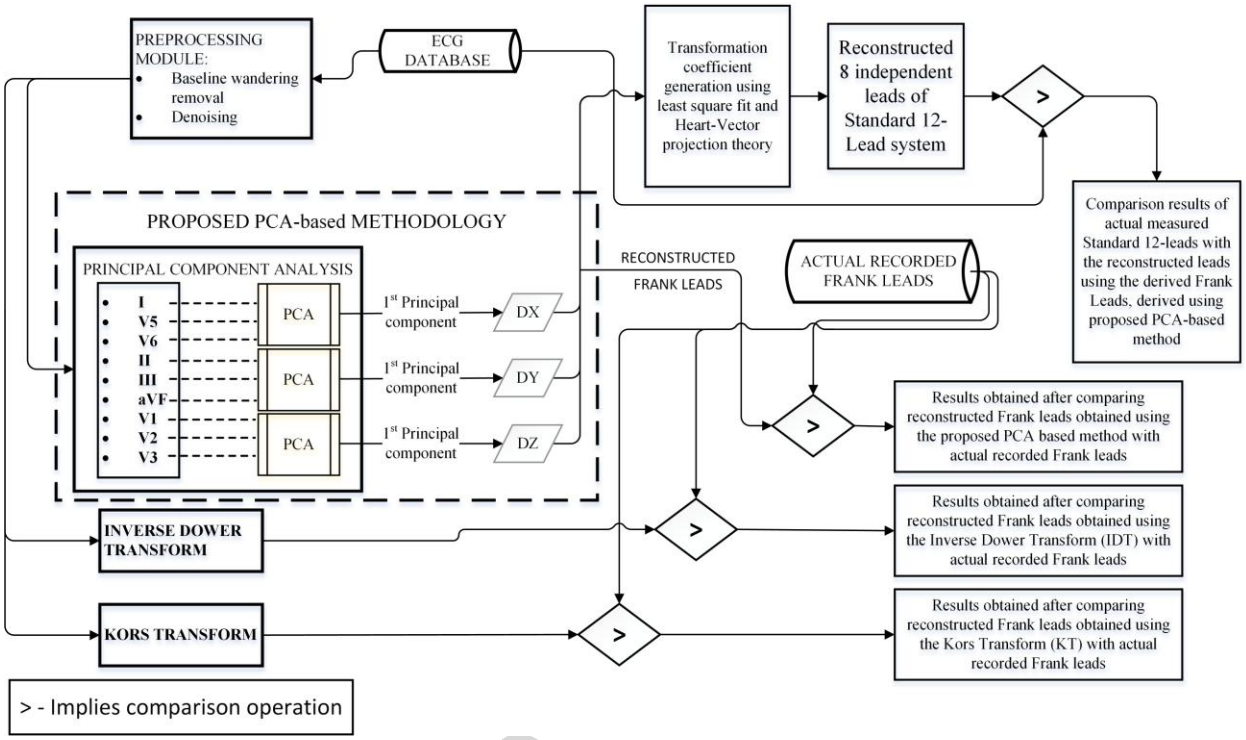

Fig. 1

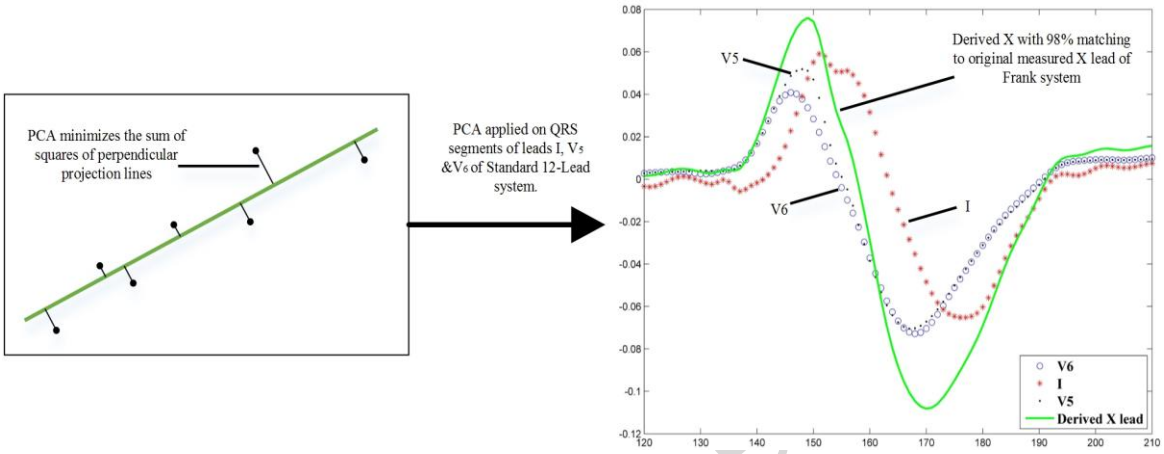

Fig. 2

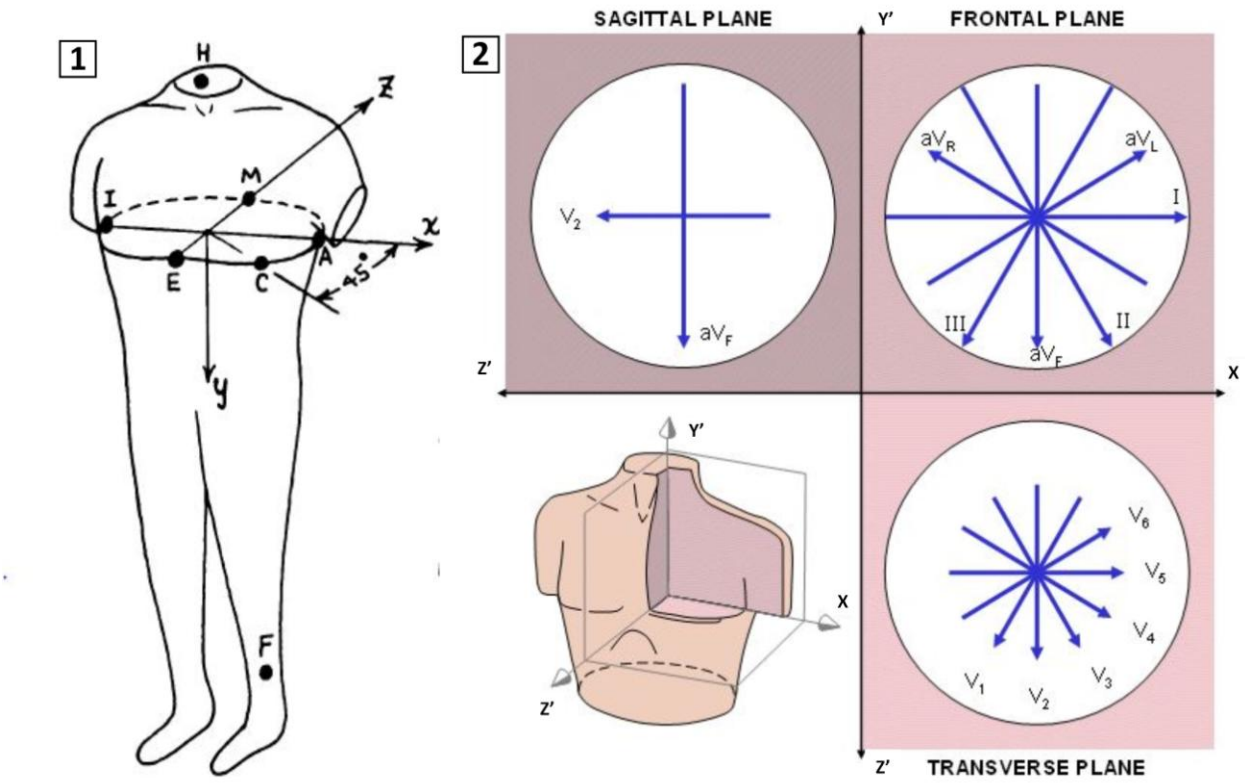

Fig. 3

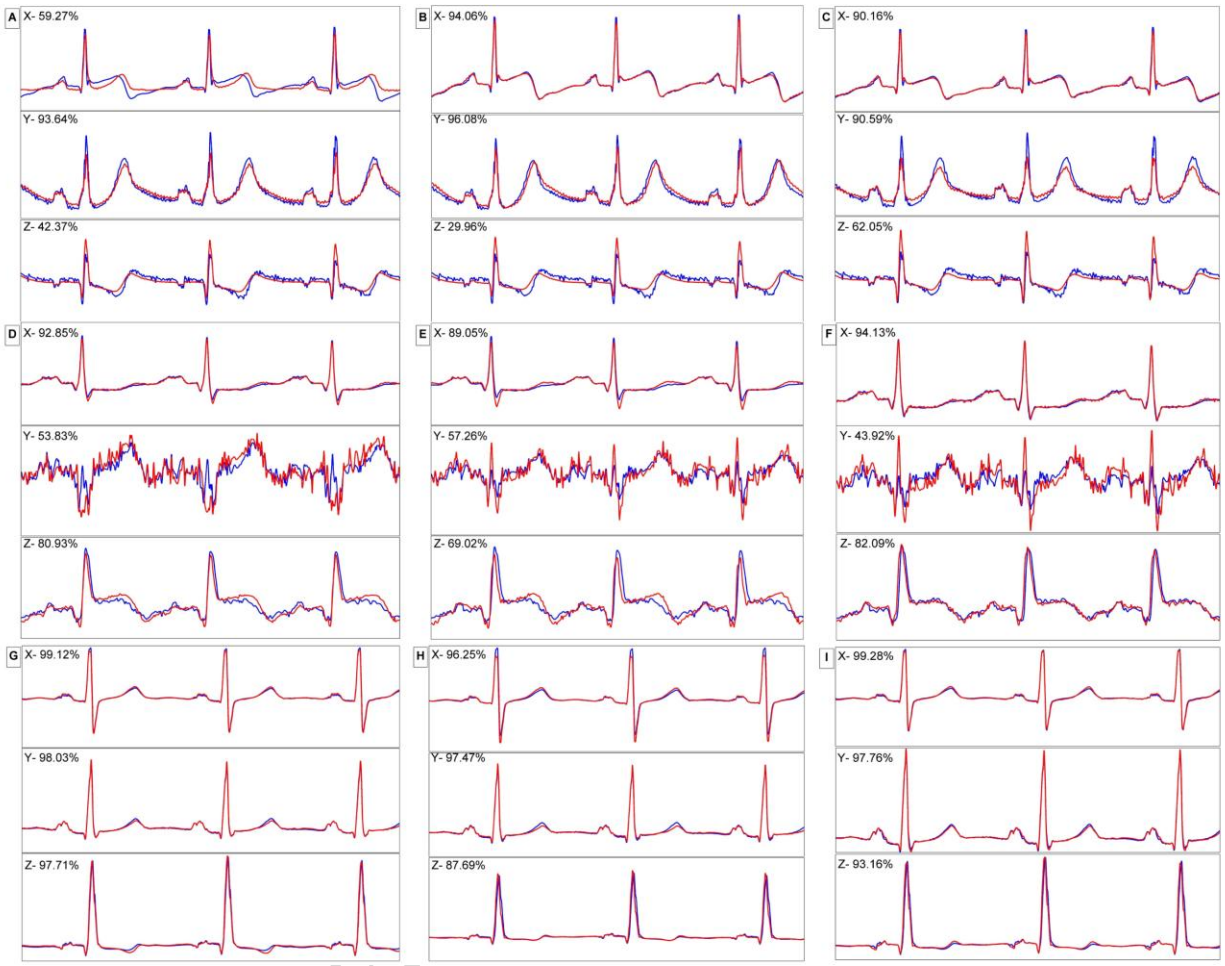

Fig. 4

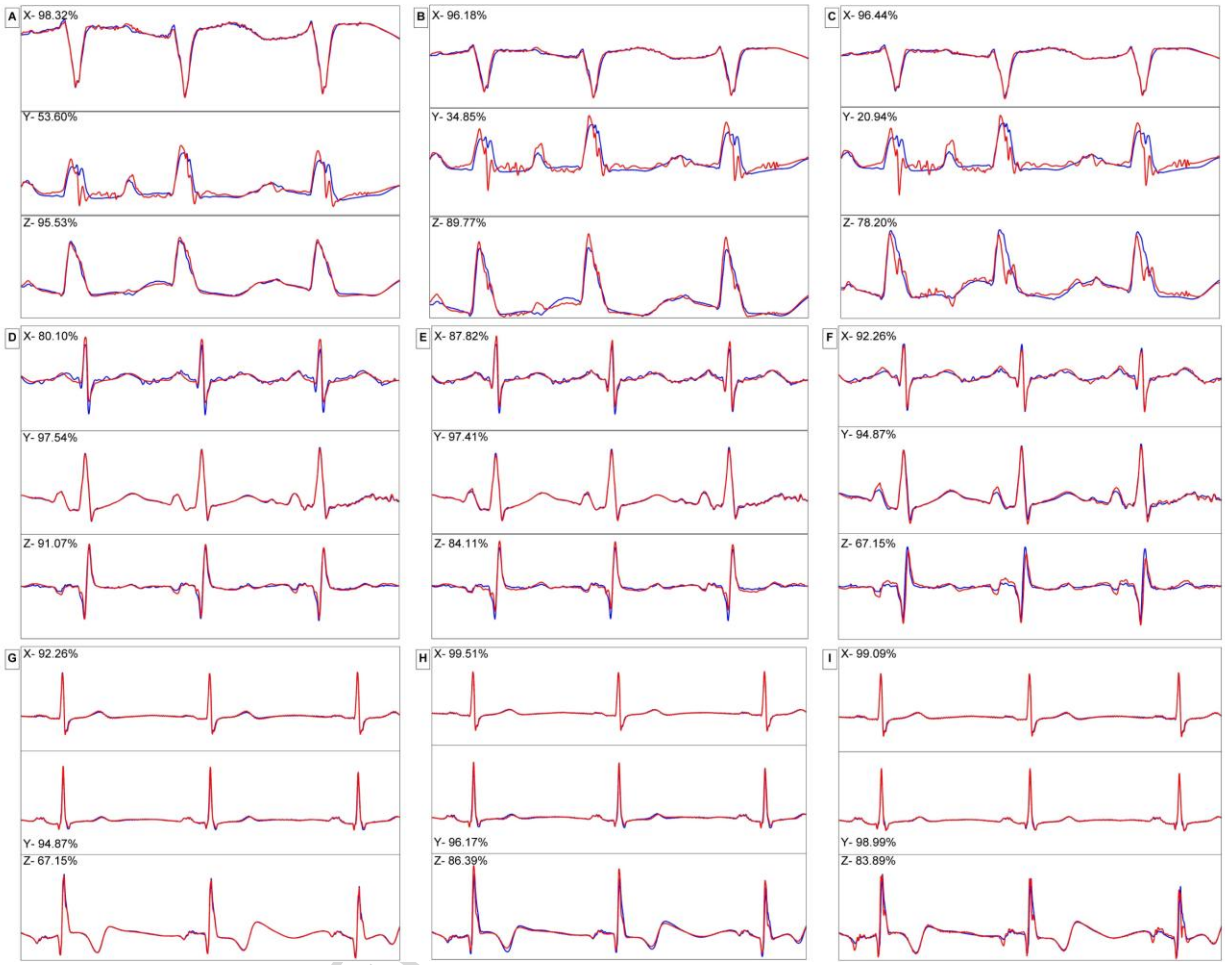

Fig. 5

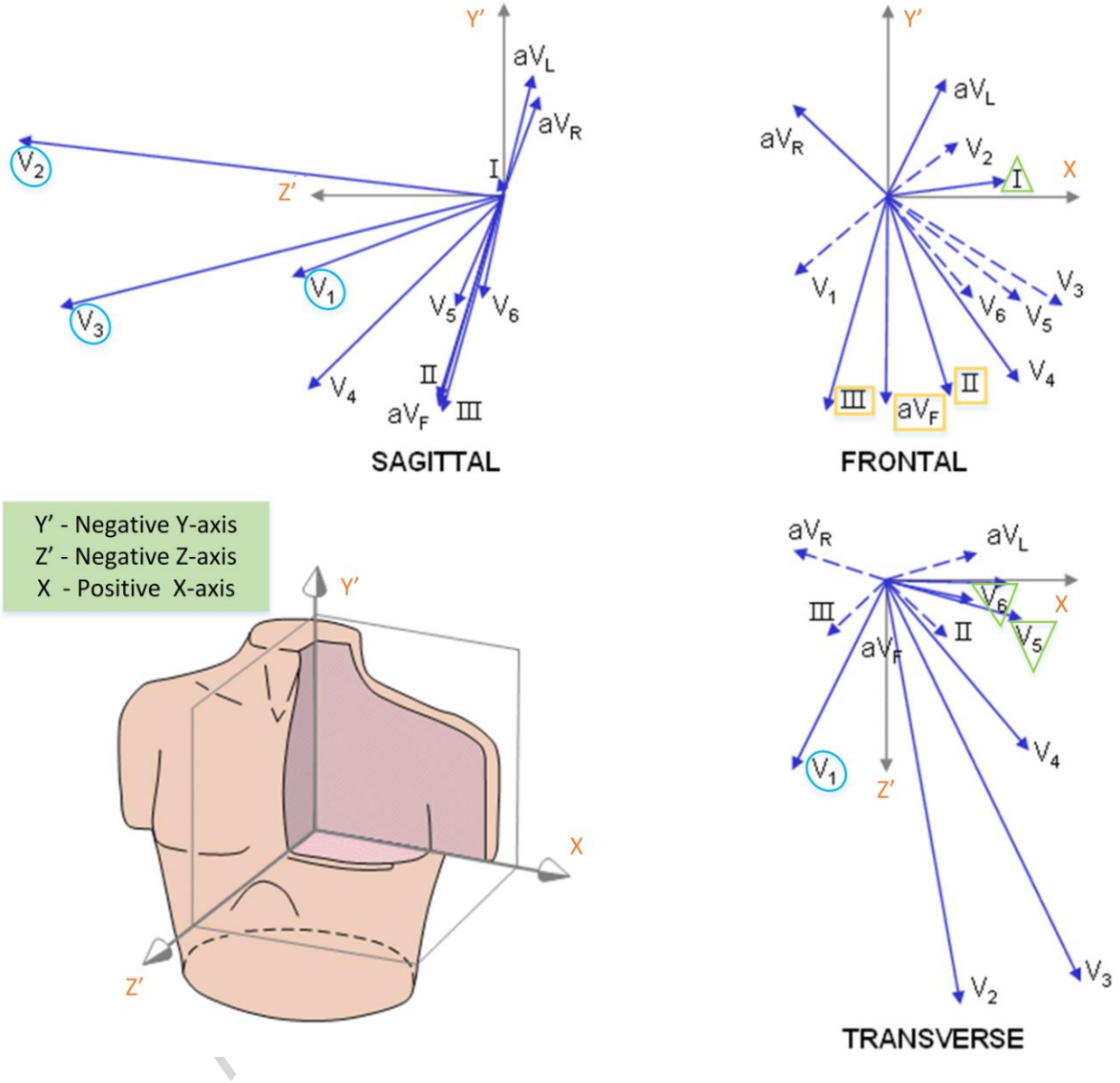

Fig. 6

Highlights

- Vectorcardiogram (VCG) has been repeatedly found useful for clinical investigation. It may not supplement but complement Standard 12-Lead (S12) ECG.
- There was tremendous research between 1950s to mid-1980s on VCG in general and Frank's System in particular, however, in last three decades it has been dropped as a routine cardiac test.
- In this paper, we propose a methodology to reconstruct Frank VCG from S12 system using Principal Component Analysis (PCA). We have compared our work with state-of-the-art Inverse Dower Transform (IDT) and Kors Transform (KT). Mean R^2 statistics and correlation coefficient values obtained for CSE multilead database (CSEDB) and PhysioNet's PTBDB using proposed method were (73.7%,0.869), for IDT (57.6%,0.788) and for KT (56.2%,0.781).
- The proposed methodology, without any modification in the current acquisition system, can be used to complement S12 system with derived Frank VCG in CVD diagnosis.
- Omnipresent computerized machines can readily apply the proposed methodology and thus, can find widespread clinical application.