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Review

The STAFF III ECG database and its significance for methodological development and evaluation

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Abstract

The development of new techniques for detection and characterization of transient myocardial ischemia has benefited considerably from the STAFF III database, acquired in patients receiving elective prolonged percutaneous transluminal coronary angiography. The present article reviews a range of techniques developed and/or evaluated on the ECG signals of this database, including techniques for exploring abnormal intra-QRS potentials, QRS slopes, QRS angles, T wave morphology, T wave alternans, spatiotemporal ECG information, as well as heart rate dynamics. The detection of changes in body position is also briefly reviewed as it is intimately related to ischemia detection.

Keywords: STAFF III database; Ischemia detection; Signal processing

Introduction

The STAFF III database is a unique set of data acquired in patients receiving elective prolonged percutaneous transluminal coronary angiography (PTCA), a procedure that belongs to the pre-stent era. The database documents the first few minutes of complete coronary occlusion. The original objective of the database was to provide a better understanding of the manifestations of myocardial ischemia in the ECG with regard to high-frequency components, particularly during ventricular depolarization. Similar to many other ECG databases, beginning with the MIT–BIH Arrhythmia Database in 1980 [1], the use of the STAFF III database has broadened considerably over the years, and it has had importance for several other research problems. Although the original study protocol of the database was designed to address a set of clinical issues, the database has turned out to be highly valuable also for developing, improving, and evaluating a wide range of signal processing techniques.

The STAFF III database is not publicly available in the sense that it can be freely downloaded and used. However, the database can be purchased at low cost by anyone in academia, as well as industry, once a brief study plan, provided by the user, has been approved by the STAFF Studies steering committee.[1] The requirement of study plan was introduced to ensure that the user is acquainted with the possibilities and limitations of the database; to date, no study plan has been turned down by the committee. The database comes with no recommendations on which methods to use when analyzing the ECG signals, but the user is expected to be in possession of the required basic algorithms, e.g., for noise reduction and beat classification, so that reliable results can be produced.

The acquisition of an ECG database can be rather easily accomplished when the recordings of interest form part of clinical routine, assuming that the recording device offers sufficient data resolution and that the ECG management system offers facilities for data export. On the other hand, the annotation, often required to make the database complete, represents a labor-intensive task, especially when multiple annotators have to deal with long-term recordings. As for the STAFF III database, the complexity of these two tasks were reversed: a dedicated, far-reaching effort was made to ensure that high resolution signals could be recorded in the catheterization laboratory, known to constitute a very noisy environment. On the other hand, no annotation was considered since the signal characteristics of primary interest, i.e., changes in high-frequency content, are extremely challenging to annotate manually, if not impossible, without having to also become dependent of the accuracy of some particular analysis method whose

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performance will compete with that of the method subject to testing.

In the present review, we trace the history of the STAFF III database with regard to methodological development and evaluation. Following a description of the database characteristics, various signal processing techniques are briefly reviewed which all have benefited from using the database. An interesting review of the STAFF Studies history, of which the STAFF III database is an essential part, can be found in this special issue [2].

The STAFF III database

The STAFF III database was acquired during 1995–1996 at Charleston Area Medical Center (WV, USA) where single prolonged balloon inflation had been introduced to achieve optimal clinical results, replacing the typical series of brief inflations. For the database, the mean inflation time was 4 min 23 s, ranging from 1 min and 30 s to 9 min and 54 s. The lead investigator Dr. Stafford Warren designed the study protocol together with Dr. Galen Wagner at Duke University Medical Center (Durham, NC, USA). The total study group consisted of 108 patients; these would account for substantial inter-patient variability in reaction to prolonged balloon inflation as well as variability in heart rhythm and waveform morphology. Only patients receiving elective PTCA in one of the major coronary arteries were included, whereas patients suffering from ventricular tachycardia, undergoing an emergency procedure, or demonstrating signal loss during acquisition were excluded.

The database consists of standard 12-lead ECG data and images obtained by injecting Technetium Tc99m Sestamibi to facilitate the detection of coronary artery disease by localizing myocardial ischemia. These images have, however, not come to play any significant role in methodological development and are therefore not considered here.

A pre-inflation ECG recording was continuously acquired for 5 min at rest in supine position in the catheterization laboratory, prior to any catheter insertion. The inflation ECG recording was started approximately 1 min before the balloon inflation, then continued throughout the inflation period, and for approximately 4 min after deflation. The occluded artery and the time instants for balloon inflation and deflation were annotated.

Standard electrode placements were used for the precordial ECG leads, whereas the limb leads were obtained with the Mason–Likar electrode configuration to reduce noise originating from skeletal muscle. While a reduced lead set would have been more convenient to employ in the catheterization laboratory, a reduced lead set would also have diminished the usefulness of the database. Data acquisition was based on a custom-made equipment by Siemens–Elema AB (Solna, Sweden) with an extraordinary dynamic input amplitude range. The ECG was digitized at a sampling rate of 1000 Hz and an amplitude resolution of 0.6 μV. These specifications ensured that high-resolution signals could be produced which rendered possible the analysis of high-frequency components as well as other subtle electrophysiological phenomena.

Ischemia detection and high-frequency QRS components

High-frequency components are mainly found within the QRS complex, characterized by an amplitude much lower than that of the waves of the standard ECG [3]. Such components have been quantified using high-resolution digital recording techniques in combination with signal averaging and filtering. Numerous studies, both on humans and animals, have investigated whether high-frequency QRS components contain information useful for diagnosing not only acute myocardial ischemia [4–7] but also myocardial infarction [8–10] and left ventricular hypertrophy [11]. Although the high-frequency ECG has received much research interest since the 1960s, this type of analysis has become commercially available only recently for clinical diagnosis of myocardial ischemia [12].

There is no standardized method for quantification of the high-frequency QRS components, although signal averaging and bandpass filtering are techniques employed in most studies. The low amplitude of the high-frequency components necessitates signal averaging so that a sufficiently low noise level can be attained. Linear, time-invariant bandpass filtering of the signal-averaged QRS complex has conventionally made use of cutoff frequencies at 150 and 250 Hz. The filtered signal, assumed to be mostly composed of the high-frequency components, is characterized by the root mean square (RMS) value of the samples within the QRS interval. The number of zones with reduced amplitudes in the filtered QRS complex, and their locations, have also been studied [13].

It is well known that bandpass filtering suffers from certain limitations, and therefore efforts have been made to develop novel techniques for more accurate analysis by making use of the STAFF III database. Linear time-invariant filtering causes ringing, irrespective of the filter phase properties, when the input signal is transient (in this case the QRS complex), thereby smearing the localized high-frequency components. As a result, the concepts of abnormal intra-QRS potentials and QRS slopes have been introduced as means to circumvent the ringing problem. Below, we will briefly consider these novel concepts, together with the QRS angles being a recent offspring of the QRS slopes.

When myocardial ischemia is elicited by balloon inflation, it is meaningful to define a performance index that reflects the magnitude of the change due to inflation. Such an index is valuable when comparing the performance of different parameters developed for ischemia detection. The ischemia detection index (IDI) is defined as the ratio between the absolute change observed during balloon occlusion and the standard deviation of the parameter of interest observed during pre-inflation [14]. Thus, the IDI can be computed in the STAFF III database, and has therefore been used in several studies mentioned below.

Abnormal intra-QRS potentials

Abnormal intra-QRS potentials (AIQPs) have been defined as low-amplitude notches and slurs (1–50 μV) or subtle alterations in the QRS complex of the signal-averaged ECG [15]. This definition was introduced in connection with the development of a technique for removing “the predictable, smooth part" of the signal-averaged QRS complex, see Fig. 1. The resulting residual signal, being a replacement of the bandpass filtered signal, was then subjected to AIQP analysis. The smooth part was modeled as the impulse response of an autoregressive model with exogenous input, and a fixed model order was selected empirically from a training dataset [16]. Since a high model order is typically required when modeling the smooth part of the QRS complex in the time domain, modeling was instead performed in the discrete cosine transform (DCT) domain since the signal energy is then packed into much fewer coefficients than the number of coefficients of the time domain [17]. As a result, a much lower model order is required with DCT-based modeling, making the method computationally more feasible. Similar to the output signal of bandpass filtering, AIQPs are quantified by the RMS value of the residual signal during the QRS interval.

On a small subset of the STAFF III database (12 patients), changes in AIQPs were investigated during balloon inflation [15]. When compared to the pre-inflation recording, a significant increase in AIQP amplitude was observed in all patients during the first minute of balloon inflation—an increase which persisted throughout inflation in most patients. A strong correlation was found between AIQPs and ST segment deviation, as well as between AIQP timing and the coronary artery occluded (AIQP timing was defined as the center of mass of the residual signal).

While the AIQPs reflect high-frequency components of the QRS complex, the reported results are opposed to those obtained using analysis based on bandpass filtering: an increase in the RMS of AIQPs is observed during balloon inflation, but a decrease in the RMS of the bandpass filtered signal. A possible explanation to the increase in AIQPs is that the QRS complex widens during ischemia, implying that the fitted model, with its fixed number of parameters estimated at baseline, has less degrees of freedom to model the widened QRS. As a consequence, the residual signal tends to increase because of reduced modeling capability, not because of an actual increase in AIQP amplitude. In this special issue, AIQP analysis is revisited but on a much larger subset of the STAFF III database [18]: the results are now in agreement with those obtained from the bandpass filtered signal, i.e., a decrease of AIQPs is observed during balloon occlusion.

The reproducibility of AIQP analysis remains to be established for patients with ischemia, especially with regard to model order since this parameter was selected empirically for each patient [15]. It is clear that too low a model order will cause the smooth part of the QRS complex to appear in the residual signal, whereas too high an order will cause AIQPs to appear in the smooth part. Several years later, a mathematical criterion for model order selection in AIQP analysis was proposed, based on the cross-correlation between the signal-averaged QRS complex and the smooth part. This criterion was evaluated on normal subjects and patients with ventricular premature contractions and sustained ventricular tachycardia (VT) [19]. In a sequel to that study, the reproducibility of parametric modeling for AIQP analysis was investigated for VT patients, the results demonstrating that VT patients exhibited a significant reduction in AIQPs when compared to those without VT [20].

QRS slopes

The steepnesses of the slopes that define the QRS complex serve as simple, indirect measures of the amount of high-frequency components: steeper slopes signify more high-frequency components, and vice versa. Starting from this observation, the upslopes and downslopes of the QRS complex were proposed as parameters for quantifying ischemia-induced changes in the ECG [21], see Fig. 2(a) for a definition of the two upslopes (US and TS) and the downslope (DS). The slope parameters can be computed directly from individual heartbeats, and thus the limitations associated with signal averaging are circumvented.

The results obtained from the STAFF III database showed that the QRS slopes became less steep during balloon inflation, especially the downslope [21]. When compared to the traditional RMS-based parameter derived from the signal-averaged, bandpass-filtered (150–250 Hz) QRS complex, the IDI was found to be considerably larger for both US and DS

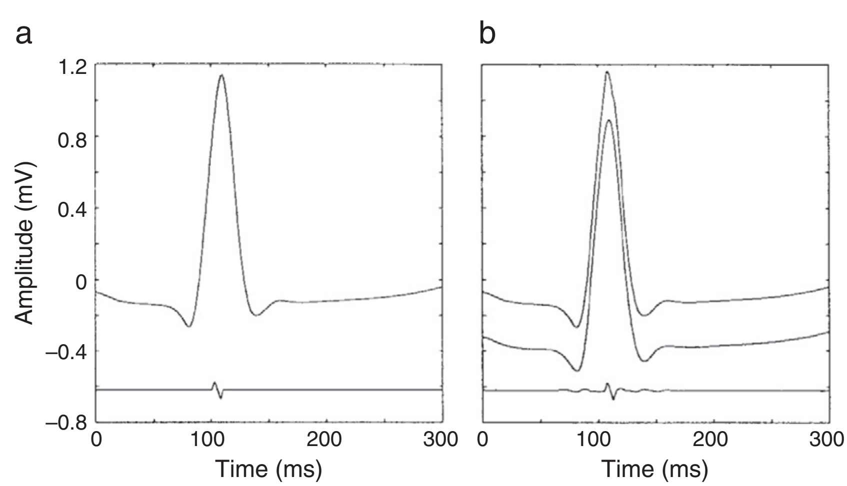

Fig. 1. (a) Signal-averaged QRS complex (top) and artificially produced AIQPs (bottom). (b) Signal-averaged QRS complex with the AIQPs superimposed (top), the smooth part of the QRS obtained by parametric modeling (middle), and the residual signal containing the AIQPs (bottom). Adapted from Ref. [15] with permission.

when computed as mean values over the database (6.9 and 7.3, respectively, versus 3.7); the upslope TS was not considered in Ref. [21]. Fig. 2(b) illustrates the changes in US and DS that take place during the first five minutes of occlusion which, in this example, are particularly pronounced in US. Even when the two cutoff frequencies of the bandpass filter were optimized for the STAFF III database, the performance gain of the slope parameters remained the same.

In a subsequent study [22], DS was shown to correlate with both extent and severity of ischemia as quantified by single photon emission computed tomography (SPECT). It was also shown that the QRS slopes provide information on ischemia which is complementary to that conveyed by the ST segment.

Since QRS morphology to various degrees is modulated by respiration [23], the slope parameters are also influenced by respiration. In terms of the IDI, such modulation implies an exaggerated standard deviation during pre-inflation and, consequently, the IDI is smaller than when modulation is absent. Therefore, a demodulation technique was developed with which the R wave amplitude was subjected to normalization so that low-frequency oscillations influencing the slopes could be attenuated [24]. Using this type of normalization, the IDI of the QRS slopes was found to improve by 27% thanks to a lower standard deviation during pre-inflation, while the ischemia-induced change in the slopes remained the same as without normalization. It was concluded that normalization improves intra-individual stability and thereby makes the slopes method better suited for detection of ischemic episodes.

Another improvement of the original slopes method was the introduction of a vectorial approach in which the slopes were determined from a new lead derived from a QRS loop rather than from individual leads [24]. The loop-derived lead was obtained by projecting the QRS loop onto the vector defining the dominant direction of the loop, i.e., the mean electrical axis. Since the STAFF III database contains 12-lead ECGs, the vector loop was produced by a linear transformation, involving either the inverse Dower matrix for synthesizing the vectorcardiogram [25], or a matrix determined by principal component analysis (PCA) [26].

When evaluating the slopes of the loop-derived lead in terms of the IDI, the results were superior to those of the 12-lead ECG [24]: US and DS were associated with IDIs equal to 10.5 and 13.7, respectively, to be compared with 6.0 and 9.3 of the best individual lead (V_3); the performance of the upslope TS was similar to DS. The performance was essentially the same whether the inverse Dower matrix or the PCA-based matrix was used, although the latter matrix was preferred since, in general, it was associated with lower standard deviation during the pre-inflation period.

QRS angles

The angles of a triangle inscribed in the QRS complex were recently proposed and evaluated as parameters suitable for detecting and characterizing acute myocardial ischemia [27]. The following QRS angles were defined: the upstroke angle, the R wave angle, and the downstroke angle, see

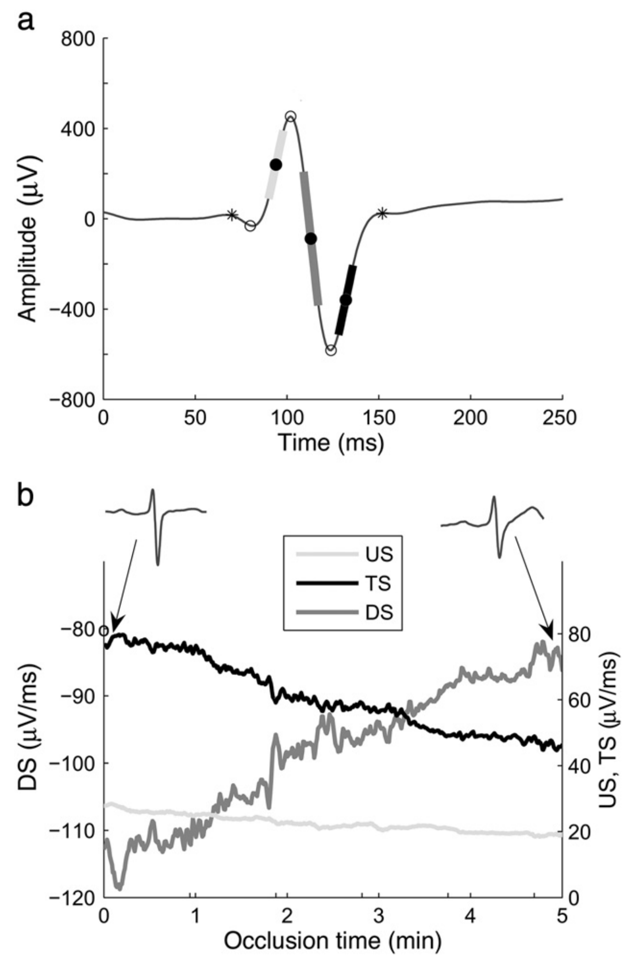

Fig. 2. (a) The definitions of the three QRS slopes, i.e., upslope (US), downslope (DS), and upslope (TS), computed in a 15-ms window centered around the time for the steepest slope. In contrast to US and DS, TS is only computed in leads V_1–V_3 and not during pronounced ischemia. (b) Trended slopes during the first five minutes of occlusion.

Fig. 3. The R wave angle can be viewed as a robust surrogate of the QRS duration, known to increase during ischemia due to slowing of the electrical activation wavefront.

The temporal evolution of the angles was investigated on the STAFF III database, the results demonstrating that the R wave angle exhibited a gradual change during balloon inflation, whereas the other two angles exhibited a much larger and more sudden change followed by stable values until the balloon was deflated. The reason for this remarkable difference in angle behavior was probably that ischemia-induced changes in QRS amplitude, shape, and width are particularly influential on the bottom edge of the triangle. As a consequence, the upslope and downslope angles exhibit larger, nonlinear changes due to ischemia, see Fig. 3. The IDIs corresponding to the upslope angle, the R wave angle, and the downslope angle were found to be 56, 65, and 18, respectively, and thus much larger than the IDIs of the QRS slopes, see above. This result suggests that the QRS angles are suitable as parameters for ischemia detection. On the other hand, only the R wave angle was useful for prediction of the severity and extent of ischemia, whereas no significant correlation was found between the upslope/downslope angles and measures of ischemia.

Ischemia detection and repolarization

Assessment of changes in the ST segment is the traditional approach to ischemia detection, relying on a set of local amplitude measurements in the standard 12-lead ECG. Since both sensitivity and specificity are known to be relatively poor for such measurements, e.g., Ref. [28], much research has been directed to finding better techniques for characterizing ventricular repolarization. With the help of the STAFF III database, a number of techniques have been developed and evaluated for such characterization, briefly considered below.

T wave morphology in individual leads

A novel method for global characterization of the ST segment was developed, offering improved noise immunity over local measurements such as ST and T wave amplitudes [14]. The clinical goal was to determine whether global characterization offers better performance when detecting ischemia. Using a set of basis functions derived from the covariance properties of a huge training set (the basis functions defined the Karhunen–Loève transform), the repolarization interval was characterized by computing the correlation between each basis function and the selected ECG interval. Fig. 4 illustrates the marked change that occurs during balloon inflation in the coefficient associated with the most significant basis function, i.e., accounting for most of the signal energy.

The results showed that the proposed approach to global characterization indeed performed better than did the local measurements when detecting ischemia: 85% of all episodes with artery occlusion in the STAFF III database were detected, whereas only 64% were detected using ST amplitude. While these results were encouraging, the basis function technique has not made its way into clinical studies, apart from two studies by the same group who investigated the identification of occluded artery [29] and the analysis of temporal evolution of the coefficients [30]. One reason may be that the information contained in the coefficients has no simple physiological interpretation.

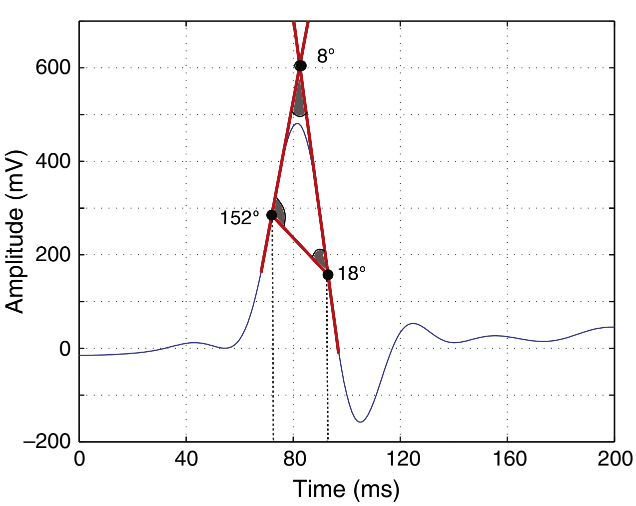

Fig. 3. Definition of the three QRS angles: the upslope angle, the R wave angle, and the downslope angle (in temporal order). The vertical dotted lines indicate the times of the maximal upslope and downslope. The details of the angle computations are found in Ref. [27].

T wave alternans

The analysis of T wave alternans aims at detecting and characterizing the tiny alterations in amplitude that occur on an every-other-beat basis, thus differing vastly from the analysis with basis functions whose aim is to quantify global changes due to ischemia. Since the signal-to-noise ratio can be poor during balloon inflation, it is crucial that the detector is based on robust signal processing techniques.

So far, only one study has investigated T wave alternans in the STAFF III database [31]. The detection method employed involved a generalized likelihood ratio test which was based on the assumption that noise can be modeled by a Laplacian distribution which better accounts for noise outliers than does the Gaussian model; as a result, more robust performance is achieved [32]. Both temporal and spatial properties of T wave alternans were investigated, including the alternans waveform that reflects the degree of alternans across the T wave interval. About one third of the patients had episodes of alternans during occlusion, most prevalent in patients with left anterior descendent artery occlusion. The onset of alternans was usually detected 1–2 min into balloon inflation, indicating that ischemia develops before alternans arises, see Fig. 5 for an illustration. Another interesting finding was that the lead distribution and alternans waveform exhibited distinct patterns for each of the occluded artery and were therefore judged to reflect the regional nature of T wave alternans [31].

Ischemia detection and spatiotemporal ECG properties

The spatiotemporal properties of the ECG during myocardial ischemia have been investigated, either jointly for the QRS complex and T wave loops [33] or for the T wave loop alone [34], see also Ref. [35]. As before, the vector loop was produced by a linear transformation defined by either a fixed or a PCA-based matrix. Both these studies showed that ischemia detection based on spatiotemporal parameters outperform the conventional ST segment parameters. In [33], the “CAVIAR serial analysis” was employed: a method which performs pairwise comparisons of two optimally aligned loops in their preferential plane [36]. Ischemia detection was based on discriminant function criteria involving the following parameters: overall spatio-temporal changes of QRS, spatial amplitude of ST60, maximum spatial amplitude of the T wave, and spatial orientation of the T wave. The diagnostic accuracy of the CAVIAR-based criteria for ischemia detection was 97% (sensitivity/specificity of 98%/96%), whereas the diagnostic accuracy of the ST segment criteria was only 74% (60%/88%). The authors concluded that spatiotemporal changes of the QRS convey information complementary to the ST changes and therefore improve ischemia detection.

Recently, repolarization dispersion was evaluated on the STAFF III database using spatiotemporal parameters to characterize the T wave [34]. The basis function technique

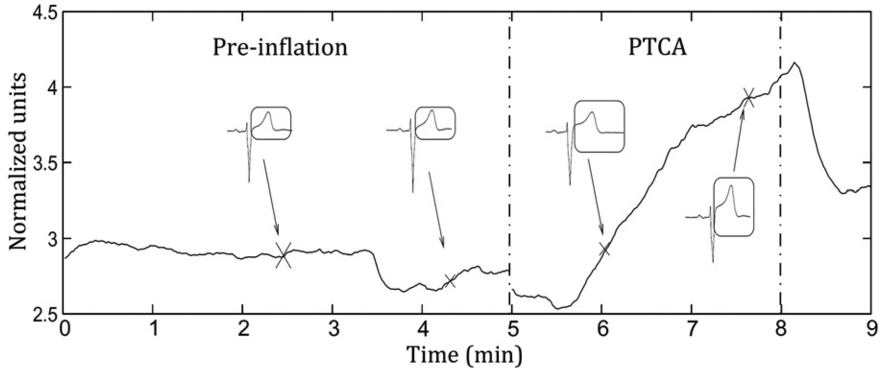

Fig. 4. Temporal evolution of the coefficient associated with the most significant basis function. The first five minutes are recorded during pre-inflation, then followed by 3 min during balloon inflation, and the last minute during deflation.

was considered for spatiotemporal analysis, analyzing the eigenvalues of the T wave in multiple leads. The three largest eigenvalues convey information on loop planarity and roundness [37]. Evaluating the detection power of lead-by-lead parameters, the largest IDIs were produced by the ratio between the two largest eigenvalues, the next largest normalized eigenvalue, and the third largest normalized eigenvalue, equal to 64, 57, and 52, respectively. The results showed that patients with T wave alternans exhibited more prominent relative changes during balloon inflation in the spatiotemporal parameters than did patients without alternans.

Ischemia detection based on spatiotemporal information was later revisited [38], but now with more focus on the particular technique employed for classification. A new classification tree algorithm was developed which relies on conditions combinations competition (T-3C) for building a multibranch tree of combined decision rules. The spatiotemporal parameters in Ref. [33] were analyzed anew. When compared to standard classification methods using a subset of leads of the STAFF III database (I, II, and V_2), the best performance was obtained for the T-3C algorithm, with a sensitivity of 98% and a specificity of 98%. Since the classification accuracy was improved over the currently recommended ECG criteria, the author concluded that tree-structured medical decision-making is a promising approach, not the least when considering that the three-lead configuration is well suited for home-based healthcare.

Heart rate dynamics

While most attention has been given to methods for investigating morphological QRST changes in the STAFF III database, a number of studies have been devoted to investigating the dynamics of heart rate during myocardial ischemia. In these studies, the aim has been to gain further insight into the dynamics through the development of parametric descriptors, rather than developing techniques for ischemia detection. Heart rate variability (HRV) during PTCA was investigated a few years before the STAFF III database came into existence [39,40]. However, this database offers certain advantages over the data used in other studies, namely, the population is larger, both pre-inflation and post-inflation recordings are available, and the balloon inflation is prolonged. The last-mentioned advantage is particularly valuable when nonlinear HRV parameters are to be computed with reasonable accuracy.

Traditional HRV parameters, defined in the time or frequency domain, have been studied on the STAFF III

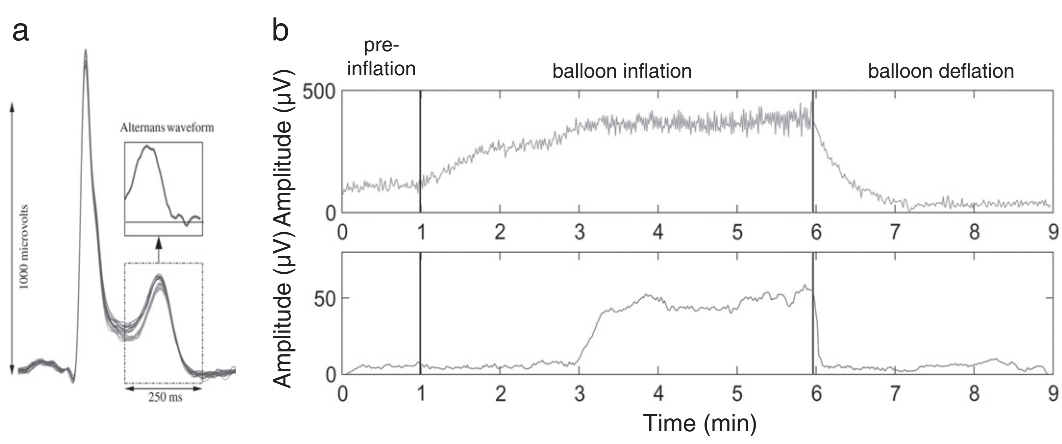

Fig. 5. (a) Superimposed heartbeats with T wave alternans, together with the alternans waveform. (b) Trends of ST amplitude (upper panel) and T wave alternans (lower panel) before, during, after balloon inflation.

database as well as parameters derived from time–frequency analysis [41,42]. Using the Choi–Williams time–frequency distribution to represent the RR interval series, a set of novel parameters were proposed which were based on the instantaneous frequency and group delay in different frequency bands (low, middle, and high) [43]. An important goal of that study was to determine whether a punctual location of the energy could be found in the time–frequency plane, useful for distinguishing different types of coronary lesions. The results showed that the proposed parameters were sensitive to ischemia, as well as dependent on the occluded artery and location.

In two subsequent studies, the same research group developed nonlinear techniques for assessing heart rate dynamics on the STAFF III database, based on information-theoretic tools and statistical inference methods [44] and multifractal analysis [45]. In the former study, a novel parameter exploring average mutual information and surrogate data was proposed for quantifying changes in the nonlinear content of the RR interval series, especially suitable for characterization of transient ischemia. Using this parameter, a statistically significant change was found in the nonlinear content during and immediately after balloon inflation. The results also demonstrated that the nonlinear effect became more pronounced when the occlusion site became more proximal, thus with more ischemic area involved. Another interesting finding was that most changes in the nonlinear content of the heart rate dynamics occur at long time scales which usually are related to sympathetic modulation of the heart rate. Using instead multifractal analysis [45], the RR interval series observed during balloon inflation and reperfusion were both associated with significant increases in the degree of multifractality, thus suggesting more complex autonomic control of the heart rate. The authors concluded that multifractal analysis is a promising technique suitable for evaluating the autonomic nervous system response during ischemia. The results of the nonlinear analysis pursued in these two studies were consistent.

Detection of body position changes

Transient changes in the ST segment are not necessarily caused by myocardial ischemia but can also be caused by a change in body position, see Fig. 6. Since this confusion is critical in intensive care monitoring where false ischemia alarms may be produced, research has been directed to developing algorithms which can detect body position changes (BPCs). With such an algorithm, it would be possible to inform the clinical staff whether the detected event is a BPC or, better, to entirely exclude any BPC-related event from further analysis.

The problem of detecting BPCs was addressed in two studies which explored spatiotemporal [46] and scalar [47] ECG information, making use of the same two databases for performance evaluation. In Ref. [46], the starting point was the well-known observation that a BPC causes a systematic shift of the electrical axis which reflects the main direction of the VCG loop, whereas a similar relationship has not been established between ischemic episodes and axis shifts. The detector analyzes shifts in loop direction, assuming that a BPC is manifested by a certain "signature" in the series of rotation angles that results from the alignment of successive loops to a reference loop [48]. The series of rotation angles is then subjected to threshold detection using a Bayesian approach.

The scalar approach to BPC detection made use of the information provided by the three most significant basis functions of the Karhunen–Loève transform, computed both for the QRS complex and the T wave [47]. A Euclidian distance is then computed between the transform coefficient vector of each heartbeat and a reference vector ("mean vector") determined at the onset of the recording. The distance is compared to a threshold having the same structure as the one of the spatiotemporal detector. The underlying assumption of the scalar detector was that BPCs are manifested as abrupt changes in the distance, while ischemic episodes are much slower.

Ideally, the performance of a BPC detector should be evaluated on data which contain both ischemic episodes and BPCs, but no such annotated database was available. Therefore, another approach was adopted to performance evaluation in which an annotated BPC database of healthy subjects was analyzed in combination with the STAFF III database. Such a dual approach to evaluation was judged as reasonable since BPCs are highly unlikely to occur during PTCA.

The spatiotemporal detector was found to perform slightly better than the scalar detector. On the BPC database, the detection probabilities were 0.95 and 0.89, respectively, whereas the same false alarm probability (0.03) was obtained for both detectors. On the STAFF III database, the false alarm rate on the pre-inflation recording was 2 and 4 events/h, increasing to 7 and 11 events/h during balloon inflation. These false alarm rates were caused by intermittent noise and artifacts, influencing the rotation angles or the Euclidian distance, and were judged to be too high for use in a clinical setting.

In a recent study, the Gaussian noise model of the scalar BPC detector was replaced by a Laplacian noise model to better account for the presence of outliers [49], cf. Section 4.2. During balloon inflation, the performance figures were improved, with detection and false alarm probabilities of 0.93 and 0.01, respectively, and a false alarm rate that dropped to 2 events/h.

Discussion

It is almost 20 years since the STAFF III database was acquired, but studies still continue to be published which make use of this unique database, whether investigating novel methodological or clinical aspects. The observation made by Moody and Mark [1] that "the MIT–BIH Arrhythmia Database has lived a far longer life than any of its creators ever expected" applies also to the STAFF III database, although the latter database has obviously not been analyzed to the same extent as the former.

The STAFF III database has served as an excellent testbed for the development of a wide range of ischemia detection techniques. However, a comprehensive comparison of the

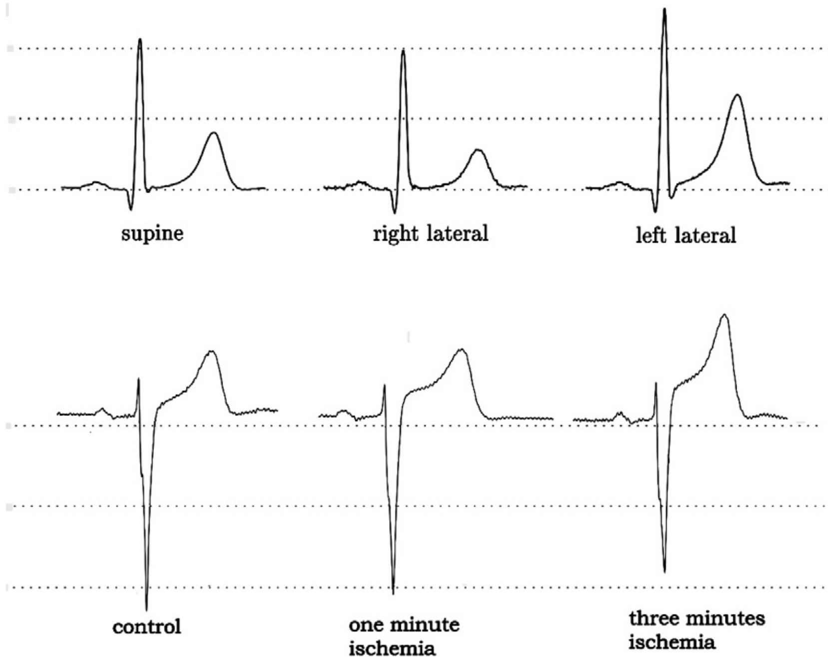

Fig. 6. Changes in the ST segment caused by either a body position change (top panel) or myocardial ischemia (bottom panel). The two examples derive from different patients.

techniques remains to be done, preferably involving not only the STAFF III database but also other databases so that information on interindividual and intraindividual variability can be further established. As has been noted elsewhere [9,24], certain parameters are associated with considerable interindividual variability which restrict their use for detection of ischemic episodes which is based on absolute, patient-independent thresholds. Nevertheless, the parameters can be useful for ischemia monitoring in those cases where patient-dependent baseline values can be determined so that relative, ischemia-induced changes can be detected.

Several publicly available ECG databases have been subjected to extensive annotation to facilitate the computation of various performance measures and, consequently, comparison of performance among different methods. As pointed out in the Introduction, the STAFF III database does not embrace any ECG annotations, e.g., QRS occurrence times, wave onset/end, and arrhythmias, since its objective is to contribute to the understanding of the manifestations of myocardial ischemia in the ECG rather than serving as a tool in the development of automated ECG analysis.

A comparison of results presented in different studies using the STAFF III database is complicated by the fact that the same set of data has not always been analyzed. Moreover, the data have not always been divided into learning and test sets, neither has cross-validation been applied although such a procedure is well motivated since the database is rather small.

Some researchers have chosen to address the problem of ischemia detection by studying parameters that are easy to interpret and that have potential to be adopted by cardiologists [41]. Hence, they preferred standard ECG parameters over KLT coefficients or wavelet coefficients to characterize the QRS complex. As already noted, the KLT coefficients have not come into widespread use, although the coefficients were found to perform much better than conventional ST parameters. Of the parameters discussed in this review, the QRS slopes and the QRS angles are both easy to interpret and may therefore have a future in clinical studies, although they do not have direct coupling to a physiological phenomenon.

To date, ischemia detection is the problem which has received most interest in connection with the STAFF III database, whereas the problem of identifying the occluded artery has received much less attention. Since the occlusion site is known, the database is valuable for evaluating the performance of identification methods. Another problem which also deserves further investigation is the relation between ECG parameters and ischemia extent/severity, quantified by the Sestamibi images.

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