Long-term ST database: a reference for the development and evaluation of automated ischaemia detectors and for the study of the dynamics of myocardial ischaemia

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Abstract—*The long-term ST database is the result of a multinational research effort. The goal was to develop a challenging and realistic research resource for development and evaluation of automated systems to detect transient ST segment changes in electrocardiograms and for supporting basic research into the mechanisms and dynamics of transient myocardial ischaemia. Twenty-four hour ambulatory ECG records were selected from routine clinical practice settings in the USA and Europe, between 1994 and 2000, on the basis of occurrence of ischaemic and non-ischaemic ST segment changes. Human expert annotators used newly developed annotation protocols and a specially developed interactive graphic editor tool (SEMIA) that supported paperless editing of annotations and facilitated international co-operation via the Internet. The database contains 86 two- and three-channel 24 h annotated ambulatory records from 80 patients and is stored on DVD-ROMs. The database annotation files contain ST segment annotations of transient ischaemic (1155) and heart-rate related ST episodes and annotations of non-ischaemic ST segment events related to postural changes and conduction abnormalities. The database is intended to complement the European Society of Cardiology ST-T database and the MIT-BIH and AHA arrhythmia databases. It provides a comprehensive representation of 'real-world' data, with numerous examples of transient ischaemic and non-ischaemic ST segment changes, arrhythmias, conduction abnormalities, axis shifts, noise and artifacts.*

Keywords—*Myocardial ischaemia, ST-segment change analysis, Non-ischaemic ST segment changes, Annotated ECG database, Performance evaluation of instrumentation, Mechanisms of transient myocardial ischaemia*

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1 Introduction

AMBULATORY ELECTROCARDIOGRAPHIC (AECG) and intensive care unit (ICU) monitoring are widely used diagnostic approaches in clinical practice for evaluating patients with suspected or known coronary artery disease. Owing to the long duration of these electrocardiogram (ECG) records, automated detection techniques are required to help in interpretation of relevant clinical events.

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Standardised reference ECG databases are important research resources that permit developers of automated detectors and ECG analysers to assess the quality of their instrumentation on the same reference database. Thus the performance of different analysers can be compared. In the early 1980s, the *MIT-BIH arrhythmia database* (MARK *et al.*, 1982) and the *American Heart Association database* (HERMES *et al.*, 1980) were released. They made it possible to develop, evaluate and compare reproducibly the quantitative performance of automated arrhythmia detectors.

Another important task during AECG and ICU monitoring is the analysis of transient ST segment and T-wave changes due to myocardial ischaemia. Improvements in recording technology since the early 1980s made it possible to begin analysis of transient ST changes during AECG. Standardising the approach

to the detection and interpretation of ST segment and T-wave changes was initiated by a 'concerted action' on ambulatory monitoring set up by the European Community in 1985 (MARCHESI, 1986). The goal was to develop an ECG database as a reference for assessing the quality of AECG analysis systems. Funding from the European Community supported development of an annotation protocol and of a small prototype database.

Development of the database was continued by the joint efforts of the Institute of Clinical Physiology of the National Research Council (CNR) in Pisa and of the Thoraxcenter of Erasmus University, in Rotterdam, with the voluntary participation of 13 research groups from eight countries that provided ECG recordings and contributed to the demanding work of annotating them. The European Society of Cardiology provided both financial and scientific backing, so as to enable completion of the European Society of Cardiology ST-T database (ESC DB) (TADDEI *et al.*, 1992*b*), which was first released in 1990. It was the first standard, generally available set of AECG records with documented 'significant' ($>100\,\mu V$) transient ST segment episodes of depression or elevation and significant transient T-wave episodes ($>200\,\mu V$) of depression or elevation.

The ESC DB contains 90 2 h, well-characterised, representative records, with manually annotated transient ST segment (368) and T-wave (401) episodes compatible with myocardial ischaemia. Episodes are annotated in each lead separately, and each heart-beat is also annotated manually in terms of QRS complex onset, beat type, rhythm change and signal quality. The ESC DB promoted further investigations in the analysis of ST-T changes in the ECG and has proven to be an invaluable resource for the development and evaluation of ECG analysers.

During the past few years, it has been a reference for companies developing biomedical equipment and has stimulated extensive research and publications (CERUTTI *et al.*, 1992; LAGUNA *et al.*, 1996; PRESEDO *et al.*, 1996*a*; EMDIN *et al.*, 1997; TADDEI *et al.*, 1997; LAGUNA *et al.*, 1997). Techniques to classify QRS complex morphology were developed and evaluated (MORABITO *et al.*, 1992; SILIPO *et al.*, 1993; 1995*a*), and a number of recognition techniques to detect transient ischaemic events automatically were introduced, including: time-domain analysis (JAGER *et al.*, 1991; TADDEI *et al.*, 1995; GARCIA *et al.*, 2000), the Karhunen–Loève transform (KLT) approach (JAGER *et al.*, 1992; LAGUNA *et al.*, 1995; GARCIA *et al.*, 1996; JAGER *et al.*, 1998*a*, SMRDEL and JAGER, 1998), non-linear principal components (DIAMANTARAS *et al.*, 1996), a variety of neural network techniques (SILIPO *et al.*, 1995*b*; SILIPO and MARCHESI, 1996; STAMKOPOULOS *et al.*, 1998; MAGLAVERAS *et al.*, 1998) and a fuzzy-logic approach (PRESEDO *et al.*, 1996*b*). A bilateral project supported by the CNR, involving the Institute of Clinical Physiology in Pisa, and the Massachusetts Institute of Technology, in Cambridge, was conducted between 1995 and 1996 to address standardisation of the analysis of ST-T changes during myocardial ischaemia.

Although the ESC DB represented a major contribution to the research community, the relatively short record lengths presented significant limitations. For example, careful analysis of the ESC DB had revealed intriguing temporal dynamics of transient ischaemic episodes (JAGER *et al.*, 1996*a*), but their full exploration was prevented by the short record lengths. The ESC DB was found to contain a number of *non-ischaemic* ST segment changes due to postural changes or slow drift of the ST deviation level (JAGER *et al.*, 1995). Such non-ischaemic ST segment episodes are quite common in real-world ECG monitoring. They complicate automated analysis of transient ST events and account for many false positive ischaemia detections. The ESC DB does not include a sufficient number of non-ischaemic episodes adequately to test the specificity of automated ischaemia detectors.

The objective of the present study was to create an annotated database of long-term ECG records that would more completely represent the spectrum of real-world ST events. Development of the *long-term ST database* (LTST DB) began in 1995 with the joint research project 'Detection of transient ST segment changes during ambulatory monitoring' (JAGER *et al.*, 1998*b*), conducted between the Faculty of Computer & Information Science, University of Ljubljana, Slovenia, and the Massachusetts Institute of Technology, Cambridge, USA. The project was sponsored by the US–Slovenian Science & Technology Joint Fund Secretariat. The project produced an initial LTST DB of 11 annotated two-lead 24 h AECG records. The aim of this database was to support the development and evaluation of ST segment change detectors capable of differentiating between ST episodes compatible with ischaemia and non-ischaemic ST events.

In 1997, Medtronic, Inc. (Minneapolis, USA), agreed to sponsor further development of the database. At that time, research groups from the Institute of Clinical Physiology, in Pisa, the Beth Israel Deaconess Medical Center, in Boston, and University Medical Center, in Ljubljana, joined the project. In 1999, Zymed, Inc. (Camarrilo, USA), became an additional sponsor of the project with a special interest in adding a set of three-lead AECG records to the database. It is important to observe that the LTST DB was not intended as a replacement of the ESC DB, but as a complement. The ESC DB was fully annotated on a beat-by-beat basis, thus supporting evaluation of algorithms for QRS detection in the presence of ST-T abnormalities, in addition to detectors of ST-segment and T-wave episodes. On the other hand, the LTST DB is of far greater size, and the annotation methodology was different. Owing to the enormous number of data, it was not practical to annotate the ST segment changes beat-by-beat. The ST segment annotations are based on average waveforms.

The goals of the LTST DB are

(*a*) more adequately to represent the wide variety of real-world data that typically challenge real-time automatic ischaemia detectors. The database should include a meaningful number of

- transient ST segment episodes compatible with ischaemia (ischaemic ST episodes)
- non-ischaemic ST episodes due to changes in heart rate (heart-rate related ST episodes)
- non-ischaemic slow ST segment drifts
- non-ischaemic ST shifts due to postural changes (axis shifts)
- non-ischaemic ST shifts due to changes in ventricular conduction (conduction changes)
- data corrupted by noise and artifacts

(*b*) to provide sufficient data in each record adequately to represent a variety of characteristic temporal patterns and dynamics of episodic ischaemia

(*c*) to include a variety of arrhythmias to support studies on their possible correlations with transient ischaemia.

In previous papers on the LTST DB, we reported our initial approach to the development of the database (JAGER *et al.*, 1996*b*), the newly established and continuously updated annotation protocols, the newly developed annotating tool SEMIA and the status of the database at that time (JAGER *et al.*, 1998*c*; JAGER *et al.*, 2000). In this paper, we present the final design and construction of the LTST DB. We present sources of AECG records, the selection procedure and selection criteria for records, the automated preprocessing procedure, the methodology to determine heart-beat fiducial points, the annotation protocols with definitions of significant transient ST events, the annotating tools, the annotating procedure using human expert annotators, the database annotations and the content of the records of the database.

2 Methods

2.1 *Sources of AECG records*

The records of the LTST DB were selected from Holter recordings obtained in routine clinical practice settings, in the United States and Europe, between 1994 and 2000. The candidate AECG records were chosen from collections of two- and three-lead AECG records at four different sites

(i) the Holter library of the Beth Israel Deaconess Medical Center, in Boston. This library represented the records of a general hospital-based cardiology department. The recordings were performed for a variety of reasons during the period of development of the database.

(ii) the Holter library from the collection of the Physiolab (Laboratory of Biosignal Processing) of the Institute of Clinical Physiology, in Pisa. This laboratory is particularly rich in examples of transient ischaemia. The laboratory provided recordings with true ischaemic and/or non-ischaemic ST segment changes from patients with ascertained coronary artery disease, other cardiac dysfunctions or conditions and non-ischaemic heart-rate related ST segment changes. This laboratory has previously contributed records to the ESC DB. In fact, 2 h excerpts of some LTST DB records from Pisa had previously been included in the ESC DB. These records had been collected since 1980.

(iii) the Holter core laboratory that processed data for the asymptomatic cardiac ischaemia pilot (ACIP) study (DAVIES *et al.*, 1997), archived at the Brigham and Womens Hospital in Boston. Patients in this study had known coronary artery disease (CAD), and the study documented a significant incidence of silent ischaemia based on Holter evidence.

(iv) three-channel Holters using the EASI lead system (Dower *et al.*, 1988) that were provided by the Zymed company. The recordings were from individuals with known CAD.

2.2 *Selection procedure and selection criteria for records*

The records of the database were selected to model real-world clinical conditions as far as possible and to document significant numbers of ischaemic and non-ischaemic ST events. The selection procedure for the records consisted of the following steps:

(*a*) the original Holter reports and sample rhythm strips were reviewed so that records with possible transient ST changes could be identified

(*b*) these tapes were then rescanned (see Fig. 1) by expert Holter technicians and cardiologists using standard Holter scanners; the digitised data from the scanner were saved; trend plots of heart rate and ST segment level, together with detailed hard-copy rhythm strips, were used to select records with ST episodes meeting one or more of the goals of the project; those records showing episodes of significant ST deviations were selected for further processing

(*c*) candidate records were further preprocessed (see Section 2.5) to produce trend plots of heart rate, ST segment deviation and KLT-based representations of the ST segment and QRS complex; expert cardiologists using the trend plots, Holter reports, original data and available clinical information selected final records for the database.

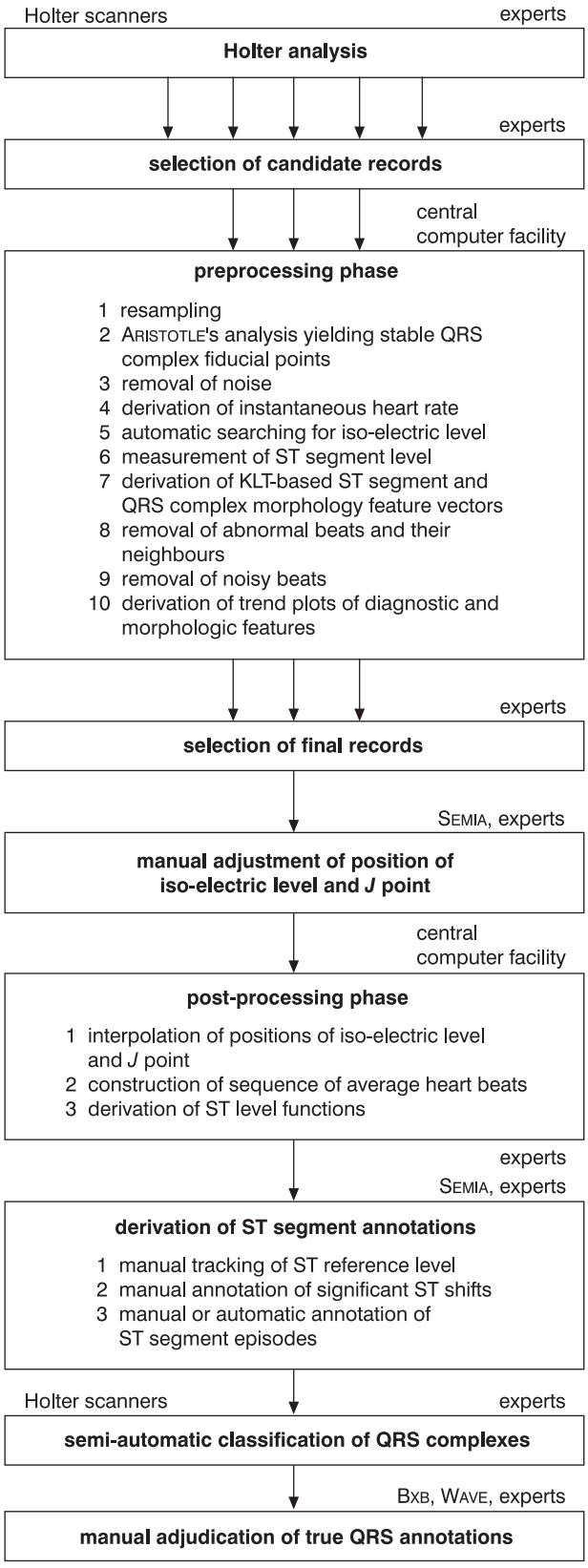

Fig. 1 *Flow of data through annotation phases and signal processing methodology of records of LTST DB*

Each selected record contained one or more of the following features: transient ischaemic ST episodes, transient non-ischaemic ST episodes due to heart-rate changes, slow ST level drifts and non-ischaemic ST shifts due to axis shifts or changes in ventricular excitation. Records containing combinations of these features were preferred. Some of the selected records contain atrio-ventricular and intraventricular conduction defects and/or arrhythmias such as atrial and ventricular ectopy, and atrial fibrillation. Other records were selected to include examples of baseline ST displacement resulting from conditions such as hypertension, ventricular dyskinesia and the effects of medications. The cardiologists also selected a number of records from patients with proven transient myocardial ischaemia, such as effort, resting, unstable, mixed and Prinzmetal's angina.

2.3 *ECG leads*

Leads that were felt to be most likely to reveal ST segment changes were generally chosen at the time of the original Holter recording. Not surprisingly therefore a variety of lead combinations were used. The leads used in the two-channel records included: precordial leads V_2, V_3, V_4 or V_5, together with modified limb lead III (MLIII); or lead V_5 and lead V_2; or modified limb lead L2 (ML2) and modified lead V_2 (MV2). The leads used in the three-channel records included: a combination from leads V_3, V_4, V_5, V_6, II and aVF, or Zymed's EASI lead system with the leads E-S, A-S and A-I.

2.4 *Recorders and sampling*

Analogue records were made using standard AECG recorders. The analogue output of the playback units was passed through anti-aliasing filters and digitised. The records were digitised at the same site as where they were obtained. As analogue AECG recorders typically preserve frequency content in the signals, typically from close to 0.05 Hz up to 30 Hz (or to 45 Hz in best cases) (BRUEGGEMANN *et al.*, 1991), the records were digitised at 128 or 250 samples per second per channel, depending on the scanning system, and the resolution was 12 bits. There is no significant information to be gained from using a higher sampling frequency for these records. The low-frequency cutoff met the AHA (KNOEBEL *et al.*, 1989) and AAMI (AAMI, 1994) recommendations. The scanning systems available and used at the sites were Marquette, ICR, Del Mar Avionics, Oxford Medilog, Remco Italia Cardioline and Zymed.

2.5 *Automated preprocessing phase*

During the preprocessing phase, which was performed at the central computer facility site at the Faculty of Computer & Information Science, in Ljubljana, time series of diagnostic and morphologic features were derived from ECG samples. The signal processing methodology is summarised in Fig. 1. The time series were needed later during the annotation phases and to derive trend plots for selecting the final records of the database. Initially, the selected records were resampled to a uniform sampling frequency of 250 samples per second per channel, and the amplitude scale was adjusted to 200 ADC units mV^{-1}. To derive morphologic features, we used the KLT, which has been proven to be useful for shape representation of the ECG morphology (MOODY and MARK, 1990; JAGER *et al.*, 1992; TADDEI *et al.*, 1992*a*).

Stable fiducial points for heart beats were generated using the ARISTOTLE arrhythmia detector (MOODY and MARK, 1982) for QRS complex detection and classification. ARISTOTLE places its fiducial point (FP) within the QRS complex region in the 'centre of mass' of deflections. In the case of a biphasic QRS complex, it is placed close to more significant deflection, whereas, in the case of a monophasic QRS complex, it is placed close to a peak of the QRS complex. A stable fiducial point in each heart beat was a prerequisite for automatic identification of the iso-electric level, calculation of KLT-based ST segment and QRS complex feature vectors, and time-averaging of heart beats. ARISTOTLE's fiducial point is stable and suitable for our further analysis.

Removal of baseline wander using a cubic spline approximation and subtraction technique and low-pass filtering by a six-pole Butterworth filter (with a cutoff frequency of 55 Hz) followed. After that, instantaneous heart rate was calculated. Next, the position of the iso-electric level in each heart-beat and in each ECG lead was defined as the centre of the 'most flat' region in the PQ interval prior to the ARISTOTLE's fiducial point (JAGER *et al.*, 1991; JAGER, 1994). After that, the ST level was measured with respect to the defined iso-electric level at the point FP + 120 ms, if the heart rate (HR) was less than 100 beats min^{-1} (or FP + 112 ms if $100 \leq HR < 110$, or FP + 104 ms if $110 \leq HR < 120$, or FP + 100 ms if $HR \geq 120$) (JAGER, 1994).

Next, abnormal beats and their neighbours were rejected, the KLT-based ST segment and QRS complex morphology feature-vector time series were derived, and noisy beats were rejected. Heart-beats were judged 'noisy' if the ST segment or QRS complex KLT feature vector differed sufficiently (mean + 1 SD) from those of the past few (15) normal heart-beats, or if the normalised residual error for the ST segment or for the QRS complex exceeded a certain percentage (25%) when the ST segment or QRS complex was approximated using the first five KLT eigenvectors (JAGER *et al.*, 1992; JAGER, 1994). The noisy beat detection procedure in the KLT space appeared to be robust and accurate. The percentage of rejected heart-beats was less than approximately 10% in almost all records.

The resulting time series were finally smoothed, resampled and further smoothed. Finally, trend plots of the time series were derived to aid in selecting the final records of the database. Morphologic KLT feature-vector time series for QRS complexes and ST segments allowed accurate visual detection of important, as well as subtle, events in the time series.

2.6 *Determining the iso-electric level and the J point*

The automatically generated iso-electric points and J points during the preprocessing phase required human editing to improve their accuracy. This was particularly true of the J points that were estimated using the ARISTOTLE's QRS fiducial points, i.e. simply 120 ms (or less, depending on heart rate) after the fiducial point. The physician annotators used SEMIA editing tools (see section 2.8) to interact with the data at a number of points in the 24 h records and manually to adjust the positions of the iso-electric level and the J point at the selected times. The flow of data through the annotation phases is shown in Fig. 1. The editing points were chosen by the annotators and were set roughly prior to, at the extrema and at the end of ST episodes; or, otherwise, approximately every 20 min. Manual adjustment of the positions of the iso-electric level and the J point was done simultaneously for all ECG leads, using average heart-beats computed over a 16 s window surrounding the points chosen for editing.

An automatic post-processing procedure estimated the positions of the iso-electric level and the J point for the remainder of the clean heart-beats by linearly interpolating between points of editing. Next, time-averaged heart-beats over 16 s intervals surrounding each clean heart-beat were computed. The *ST level function* was then constructed in each lead using the adjusted iso-electric and J points. ST amplitudes were measured at J + 80 ms if HR was less than 100 beat min^{-1} (or J + 72 ms if $100 \leq HR < 110$, or J + 64 ms if $110 \leq HR < 120$, or J + 60 ms if $HR \geq 120$). The ST level functions were then resampled (0.5 samples s^{-1}) and smoothed (7-point moving average). Finally, these new ST level functions replaced those derived during the preprocessing phase and formed the basis for annotating ST events.

2.7 *Annotation protocol*

The annotation protocol is compatible with that developed for the AHA, MIT-BIH arrhythmia and ESC databases, but we have extended it to permit more detailed descriptions of non-ischaemic ST events. The ST events were defined and annotated independently in each ECG lead to support analysis of each ECG lead independently and also to enable evaluation of single-lead ischaemia detection algorithms. Electrocardiogram waveform analysis alone is often inadequate to make an unambiguous diagnosis of myocardial ischaemia and should

not exclusively be relied upon for annotating transient ischaemic ST change episodes. Therefore our gold standard for annotating transient ischaemic and heart-rate related ST segment episodes was the expert cardiologists' opinion, based on: their knowledge and experience, type of change of ST segment waveforms, 24 h context of diagnostic and morphology parameters, and detailed clinical information from the subjects, including other clinical investigations and clinical history. The basis for annotating ST events in each ECG lead was the ST level function (see Fig. 2). The ST level function typically varies widely and significantly in amplitude, owing to drifts, position changes, changes in conduction, heart-rate related changes and ischaemia.

The annotators defined several *classes* of ST segment changes

(i) *non-ischaemic changes in ST segment morphology*
- slow or sudden changes due to simultaneous slow or sudden (postural - axis shifts) changes in the cardiac QRS electrical axis; these are characterised by a change in the Q-, R- or S-wave amplitude
- slow or sudden changes due to paroxysmal or intermittent right or left bundle branch block, or other slow or sudden intraventricular or intermittent QRS conduction changes; these are characterised by bizarre and wider QRS complexes
- slow drifts due to heart-rate related diurnal changes or effects of medication on repolarisation; drifts are characterised by slow and persistent typical non-ischaemic changes in ST segment slope and shape within a longer period, and may or may not be accompanied by a change in heart rate

(ii) *non-ischaemic heart-rate related change in ST segment morphology*: this is characterised by changes in ST segment morphology and by a change in heart rate, when clinical information from the subject does not suggest ischaemia. Typically, and most often, changes in ST segment morphology of this class include: J point depression with positive slope; moving of T-wave into ST segment; T-wave peaking; or parallel shift of ST segment compared with the reference or basal ST segment

(iii) *ischaemic change in ST segment morphology*: this is characterised by changes in ST segment morphology and may or may not be accompanied by a change in heart rate, when clinical information from the subject suggests ischaemia. Typically, and most often, changes in ST segment morphology of this ischaemic class include: horizontal flattening; down sloping; scooping; or elevation

(iv) *noisy ST event*: this is characterised by consecutive ST segments that cannot be evaluated by annotators because of noise.

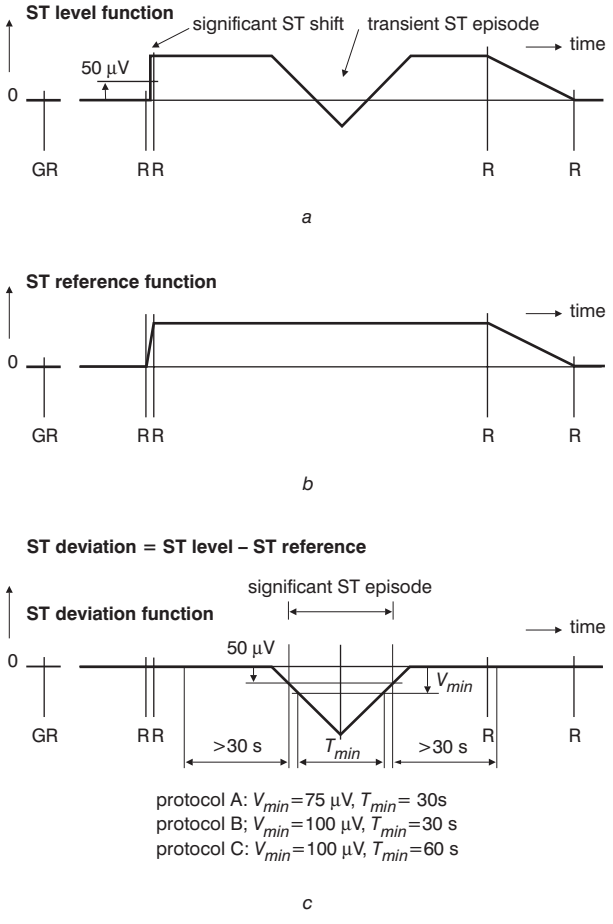

Fig. 2 *Definition of significant ST shift and significant ST episode, schematic representation of tracking of ST reference level and representation of annotation protocols. (a) Manual tracking of time-varying ST reference level in ST level function of ECG lead, except for deviations due to transient ST episodes. Local-reference annotations are placed at intervals in non-ischaemic data. (b) Straight-line segments connecting local-reference annotations produce ST reference function. (c) ST deviation function is obtained as change in ST level function from which ST reference function is subtracted. GR = global reference; R = local reference*

Record annotation began with the establishment of the *global-reference* annotation in each ECG lead (refer to Fig. 2). It was chosen to be near the beginning of the record, at a time when the ST level was stable for at least 5 min. All subsequent ST annotations were referenced to the global reference level. The next step in the annotation process was manually to track the time-varying ST level, except for deviations due to ischaemia, non-ischaemic heart-rate related changes in ST morphology and noisy ST events. The tracking process permitted the human experts to remove from consideration variations in ST level that could also be significant ($>50\,\mu V$) but were clinically not important. Annotations (known as *local references*) were placed at intervals in the non-ischaemic data and were connected with straight-line segments to produce the *ST reference function*. The algebraic difference between the ST level function and the ST reference function was the *ST deviation function*, which clearly identified transient ST deviations from the local ST reference level, as defined by the annotators. Ischaemic and non-ischaemic heart-rate related ST episodes were then identified and annotated in the ST deviation function. To be annotated, a transient ST episode had to be significant, satisfying the following criteria:

- an episode begins when the magnitude of the ST deviation function first exceeds 50 μV
- the deviation must reach a magnitude of V_{min} or more throughout a continuous interval of at least T_{min} s
- the episode ends when the deviation becomes smaller than 50 μV, provided that it does not exceed 50 μV in the following 30 s.

Different values for V_{min} and T_{min} were used, yielding three different ST annotation protocols. Protocol *A* included: $V_{min} = 75\,\mu V$, and $T_{min} = 30$ s; protocol *B*: $V_{min} = 100\,\mu V$, and $T_{min} = 30$ s; and protocol *C*: $V_{min} = 100\,\mu V$, and $T_{min} = 60$ s. Thus three sets of ST episode annotations were provided, as differing criteria may be appropriate, depending on the application.

To annotate ST events successfully, the annotators considered ST level and ST deviation functions, the original ECG signals, the time series of QRS complex and ST segment KLT coefficients and clinical information about the patients (final diagnosis, other investigations, patient history). The annotators used

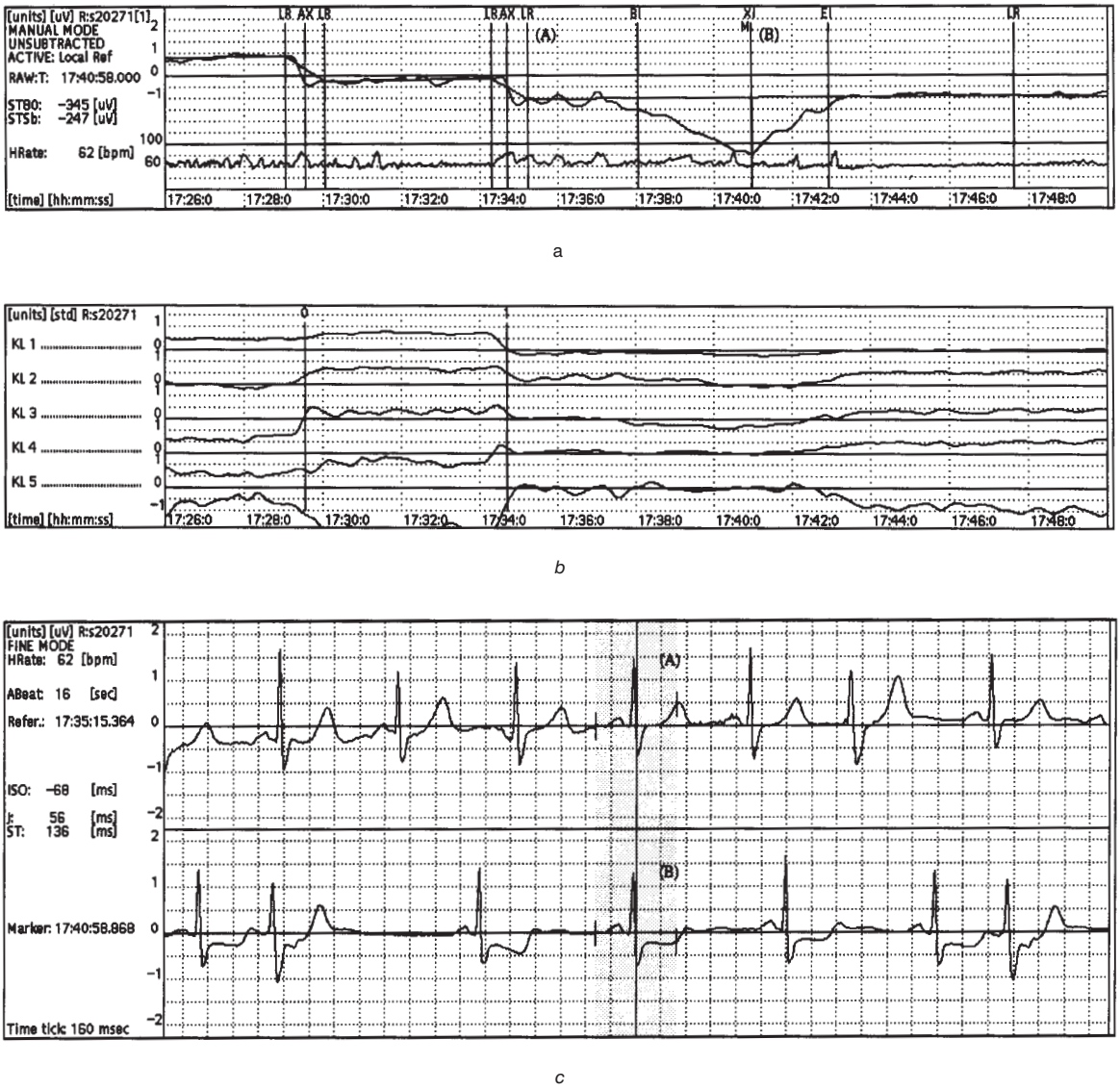

Fig. 3 *Example of annotation of lead 1 in record s20271 from time 17:26:00 to 17:50:00. Abbreviated* SEMIA*'s 'lead' 'KLT' and 'data' windows (from top to bottom) are shown. (a) ST level function (resolution: 100* $\mu V\,unit^{-1}$*) and piecewise linearly interpolated ST reference function (above), heart rate (below), local reference annotations (LR) defining knot points in ST level function, axis shift annotations (AX) indicating significant ST shifts, and ST episode annotations (BI, XI, EI) indicating significant ischaemic ST episode according to protocol A. (b) Time series of first five (from top to bottom) QRS complex KLT coefficients (resolution: 1 SD* $unit^{-1}$*), and markers 0 and 1 corresponding to both axis shift annotations. (c) Original ECG signals (resolution: 1* $mV\,unit^{-1} \times 160\ ms\,unit^{-1}$*) corresponding to local reference (LR) prior to ischaemic ST episode ((A); time: 17:35:15.364) and to extrema (XI,M) of ischaemic ST episode ((B); time: 17:40:58.868), where centre heart beats are time-averaged heart beats over 16 s*

SEMIA editing tools to support their analysis. An example of annotating is shown in Fig. 3. For the annotation phases, refer also to Fig. 1. The ST segment level was tracked in the cases of slow drift or in the cases of other non-ischaemic changes in ST segment morphology, which had to be evident by simultaneous change in QRS complex morphology and also evident in the time shape within a longer period, and may or may not be accompanied by a change in the course of the QRS complex KLT coefficients. Any significant, sudden step-change of the ST level function that was accompanied by a simultaneous sudden step-change in QRS complex morphology was bounded by a local reference before and after the step change and was annotated as *significant axis shift* or *significant conduction change*, according to its nature.

Significant ST episodes associated with non-ischaemic heart-rate related changes in ST segment morphology (defined above) were annotated as *significant heart-rate related ST episodes*. Episodes associated with ischaemic changes in ST segment morphology (defined above) were labelled as *significant ischaemic ST episodes*. Sometimes, significant axis shifts or conduction changes appeared within significant ST episodes. In these cases, they were not tracked out, but were annotated within the episodes. Sometimes, significant ST episodes were caused by noisy ST intervals. Short, noisy episodes were annotated as *noisy events* at their extrema, and longer noisy periods were annotated as *unreadable intervals*. Longer intervals with all heart-beats rejected during preprocessing because of noise were also annotated as unreadable intervals.

2.8 *Annotating tools*

SEMIA (semi-automatic) is a special-purpose graphic event-driven user interface and signal-processing tool designed especially for this project (JAGER *et al.*, 1998*c*; 2000) The system is a powerful graphical editing system and was critical to the success of the annotation process. An abbreviated

display of SEMIA's windows is shown in Fig. 3. SEMIA'S display provides the annotator with a global view (at different resolutions) of the ST deviation function and heart rate, a close-up view of individual heart-beat waveforms and a view of the temporal course of KLT coefficient representations of the QRS complexes and ST segments. SEMIA supports: manual adjustment of heart-beat fiducial points, manual tracking of the ST reference level, annotation of significant ST shifts, and manual or automatic annotation of ST episodes according to selected criteria. SEMIA supported database annotation at different geographical sites interacting via the Internet and without paper tracings.

2.9 *Annotating procedure and expert annotators*

After setting local references and annotations indicating significant ST shifts (see Fig. 1), the expert cardiologists of the team R.G. MARK, M. EMDIN, and G. ANTOLIČ reviewed and corrected the ST reference functions, automatically annotated significant ST episodes in the ST deviation function using SEMIA and then manually verified and corrected ST episode annotations. The three expert annotators worked independently at three different sites: Boston, Pisa and Ljubljana. They reached consensus on the annotations at seven joint meetings held during the project.

2.10 *True QRS annotations*

True QRS annotations for the selected records of the database were obtained as follows: Records were rescanned once again (see Fig. 1) by two independent Holter technicians, one using a Marquette Holter scanner and the other using a Zymed Holter scanner. Each of the Holter technicians identified all QRS complexes in each record during scanning and manually corrected the type of those QRS complexes that were falsely classified by the scanner. The output of the scanners was QRS annotation streams containing fiducial points of QRS complexes and QRS annotations according to their beat types. The two QRS annotation streams for each selected record were then merged together beat-by-beat into one annotation stream using the BXB program of the WFDB utility software (MOODY and MARK, 1991). The program keeps both QRS annotations for an individual QRS complex, if the QRS annotations from the two annotation streams for this QRS complex differ. Discrepancies in the individual QRS annotations were then adjudicated manually by an expert cardiologist using the WAVE tool of the WFDB.

3 Results

3.1 *Database annotations*

The LTST DB record files are in the WFDB format (MOODY and MARK, 1991). They contain detailed clinical information for the patients, waveform data, true QRS annotations and ST annotations that are easily accessible by the WFDB software. Record files are summarised in Table 1.

The header file (.hea) describes the format of the signal files (.dat) and contains technical information about the record (recorder, date and starting time of recording, leads), comments of expert annotators and a detailed and compact clinical summary for the patient. The clinical summary includes age, sex, the Holter report on symptoms during recording, final diagnosis, previous coronary angioplasty or by-pass, and current medications. Factors that could affect ST-T morphology were also documented, including known heart disease (coronary heart disease, angina, previous myocardial infarction, valvular heart disease, left ventricular hypertrophy, cardiomyopathy, AV nodal or intraventricular conduction delay or block etc.), hypertension, electrolyte abnormalities, hypercapnoea, hyperventilation, hypotension or anaemia. The clinical summary also includes reports of previous clinical investigations that have been performed (baseline ECG, stress ECG, thallium positron emission tomography or scintigraphy, stress echo, left ventricular function echocardiography and coronary arteriography).

Table 1 Files of LTST DB records

File	Content
s*N*xxxy.hea	header
s*N*xxxy.dat	signals
s*N*xxxy.ari	ARISTOTLE's QRS annotations
s*N*xxxy.atr	true QRS annotations
s*N*xxxy.sta	ST segment annotations (protocol A)
s*N*xxxy.stb	ST segment annotations (protocol B)
s*N*xxxy.stc	ST segment annotations (protocol C)
s*N*xxxy.cnt	numbers of annotated ST events
s*N*xxxy.16a	ST segment measurements

N = number of ECG leads (2 or 3); xxx = patient number; y = record number

ARISTOTLE's QRS annotation file (.ari) contains automatically derived QRS annotations and QRS complex fiducial points. The true QRS annotation file (.atr) contains human QRS annotations. The annotation codes used for these two QRS annotation files are the same as those in the MIT-BIH database (MOODY and MARK, 1991). The ST segment annotation files (.sta, .stb, .stc) contain ST segment annotations (see Table 2) according to annotation protocols A, B and C. The numbers of ST episodes, as determined by each of the three sets of criteria, and the number of significant ST shifts are summarised in the (.cnt) text file. The ST segment measurements file (.16a) contains measurements obtained on average heart-beats comprising clean heart-beats (those that passed the preprocessing phase) in 16 s averaging windows. An annotation contains: the value of the ST level function for that average heart-beat; ST segment amplitude measurements at the points: J + 0 ms, J + 20 ms, J + 40 ms, J + 60 ms, J + 80 ms, J + 100 ms and J + 120 ms; positions of the iso-electric level and J point relative to the QRS fiducial point for this average beat; and the number of heart-beats left and right of the centre heart-beat included in the corresponding average beat.

3.2 *Database records*

The LTST DB contains 86 AECG records from 80 patients with significant transient ST events annotated by human

Table 2 ST segment annotation codes used for LTST DB

Code	Meaning
GRST *n*	global reference
LRST *n* ± llll	local reference
s [cc] st *n*	significant ST shift
([rt] st *n* ± dddd	beginning of significant ST episode
a [rt] st *n* ± dddd	extrema of significant ST episode
[rt] st *n* ± dddd)	end of significant ST episode
noi *n* ± dddd	noise
(urd *n*	beginning of unreadable interval
urd *n*)	end of unreadable interval

[cc] = type of ST shift (none = axis shift, cc = conduction change); [rt] = type of ST episode (none = ischaemic, rt = heart-rate related); *n* = lead number (0, 1 or 2); llll = ST level, μV; dddd = ST deviation, μV

Table 3 Records of LTST DB: 80 patients in 86 records. Patients' data with numbers of annotated ST segment events according to annotation protocol A are presented

Record	S	A	Diagnosis	Ischaemia	HR	ST/I	A/C
s20011	M	58	NoCAD	0,0	14,6	15/0	0,7
s20021	M	55	PMA	20,26	0,0	26/26	2,37
s20031	M	55	CAD,PMI	5,5	6,7	12/5	0,0
s20041	M	60	CAD,CHF, COPD,CRF,PCABG,PTURP	26,30	0,0	28/28	5,6
s20051	F	87	HTN	2,0	0,0	2/2	24,1
s20061	F	33	SY	0,0	26,0	26/0	0,0
s20071	F	41	Pgn,SY	0,0	9,4	9/0	0,0
s20081	F	39	PPT	33,0	0,24	32/33	7,9
s20091	F	34	Pgn,PPT	0,0	23,7	27/0	0,0
s20101	F	62	CAD,A,HTN	1,2	0,0	2/2	2,0
s20111	M	64	CAD,AAA,BPH,PRT,SYE	7,0	11,2	18/7	13,1
s20121	F	48	3-VCAD,HL,IDDM,PAI,PCVAx4,PFPB	9,0	0,0	9/9	15,8
s20131	F	82	3-VCAD,ILMI,LVDD	31,0	0,4	26/31	2,0
s20141	F	35	PPT	0,0	44,48	47/0	0,10
s20151	M	62	CAD,PMA	33,39	0,0	43/43	7,1
s20161	M	65	CAD,PMA	59,10	0,0	59/59	16,2
s20171	M	44	CAD,HTN,PMA	24,8	0,0	25/25	13,8
s20181	M	66	CAD,EA,RA	0,36	0,0	36/36	74,20
s20191	M	66	CAD,PMA	5,3	0,0	5/5	0,0
s20201	F	78	SY,SZ	0,0	7,0	7/0	20,2
s20211	F	34	SY	0,0	19,11	18/0	10,19
s20221	M	57	HTN,LVH,PFO,TIA	0,0	4,0	4/0	70,95
s20231	M	53	AF,CHF,COPD	0,0	3,6	4/0	1,4
s20241	F	29	MVP,PPT	0,0	10,15	11/0	0,0
s20251	M	65	CAD	2,5	0,0	5/5	0,0
s20261	?	??	CAD	17,13	0,0	18/18	18,13
s20271	M	61	CAD	63,62	0,0	63/63	20,32
s20272	M	61	CAD	25,33	0,0	33/33	5,33
s20273	M	61	CAD	35,55	0,0	53/53	2,15
s20274	M	61	CAD	55,88	0,0	88/88	0,15
s20281	M	68	CAD	14,2	0,0	14/14	0,0
s20291	M	47	CAD,PMA	32,37	0,0	38/38	3,19
s20301	M	58	CAD,PMA,PSMI	41,0	0,0	41/41	44,8
s20311	M	48	PMA	9,10	4,44	52/9	2,34
s20321	M	73	CAD,EA	2,3	0,0	3/3	0,2
s20331	M	85	RA	6,0	0,0	6/6	21,0
s20341	F	77	CAD,HTN,SS,SY	8,0	0,0	8/8	0,2
s20351	M	62	CAD,HC,PMI	4,5	1,1	6/5	3,0
s20361	M	63	CAD	2,2	0,0	2/2	0,0
s20371	M	64	CAD	9,0	0,19	24/9	24,11
s20381	?	??	CAD	1,1	3,0	4/1	0,0
s20391	M	64	CAD,IDDM	2,3	0,0	2/2	25,23
s20401	M	44	CAD	9,7	0,0	7/7	1,1
s20411	F	67	CAD	9,14	0,0	14/14	0,5
s20421	M	80	CAD	0,20	0,0	20/20	0,6
s20431	M	74	CAD	15,13	14,0	28/14	13,5
s20441	M	64	CAD	8,14	0,0	14/14	0,4
s20451	?	??	CAD	4,4	0,0	4/4	4,0
s20461	?	??	CAD	4,4	0,0	4/4	0,0
s20471	M	56	HTN,PMA	1,1	2,2	2/1	9,6
s20481	F	71	CAD,EA,HTN,RA	7,0	0,0	7/7	1,1
s20491	M	70	CAD	6,1	0,0	6/6	0,0
s20501	F	63	OHCM	0,0	0,0	0/0	112,120
s20511	F	61	CAD,UA	8,5	0,0	8/8	0,0
s20521	M	45	NOHCM	0,0	8,1	9/0	12,2
s20531	M	70	DCM	0,0	0,0	0/0	0,0/232,218
s20541	F	23	WPW	0,0	11,5	11/0	0,0/281,148
s20551	F	77	CAD,HTN,LBBB	4,1	0,0	3/3	1,4/2,2
s20561	M	79	CAD,AF,HTN,	8,0	0,0	8/8	0,0
s20571	M	76	CAD	10,0	0,0	10/10	0,0
s20581	M	61	3-VCAD,HTN,RA	2,1	0,0	2/2	4,1
s20591	M	49	CAD,MA,MI	54,3	0,0	54/54	2,0
s20601	F	46	SyX	1,3	0,0	3/3	0,1
s20611	F	59	HTN	0,43	0,0	43/43	0,0
s20621	F	31	MVP	0,0	19,17	15/0	5,1
s20631	M	47	HC	0,0	4,1	4/0	50,4
s20641	F	34	MS	0,0	5,5	6/0	0,0
s20651	M	84	CAD,AAMI,HTN,LVF	0,0	19,2	19/0	6,17
s30661	M	72	2-VCAD,BPH,COPD,HTN,LIMA-LADCA, PCABG,UA	21,19,8	0,0,0	22/22	3,4,1

s30671	M	52	CAD,A,IDDM,PMI	9,14,5	0,0,0	14/14	0,0,0
s30681	M	71	CAD,MHTN	26,11,30	0,0,0	29/29	0,0,0
s30691	F	81	CAD,LHTN,PPT	7,22,11	0,0,0	22/22	0,0,0
s30701	M	67	CAD	3,2,4	0,0,0	2/2	1,2,1
s30711	?	??	CAD	5,27,18	0,0,0	27/27	0,0,0
s30721	F	85	CAD,HL,OA	0,1,1	2,0,0	3/1	0,0,0/0,7,5
s30731	M	82	CAD	0,4,6	0,0,0	6/6	6,26,20
s30732	M	82	CAD	0,1,1	0,0,0	1/1	12,26,27
s30741	F	54	CAD,ASTH,CHF,CVA,HTN	17,11,18	0,0,0	20/20	0,0,0
s30742	F	54	CAD,ASTH,CHF,CVA,HTN	18,18,19	0,0,0	19/19	0,0,0
s30751	M	79	CAD	7,2,3	0,0,0	7/7	1,6,2
s30752	M	79	CAD	2,0,2	0,0,0	4/4	0,6,3
s30761	F	72	CAD,A,HC,HTN,PMI	0,25,7	0,0,0	24/24	0,0,0
s30771	F	75	CAD,PMI	3,9,9	0,0,6	16/14	0,8,9
s30781	F	84	CAD,HL,PCABG	0,1,1	10,1,0	11/1	0,4,3
s30791	M	74	CAD,A,HTN	6,3,4	0,0,0	5/5	14,12,10
s30801	M	59	CAD,HL,HTN	0,4,6	0,0,0	6/6	1,0,2

s*N*xxxy: *N* = number of ECG leads (2 or 3), xxx = patient number, y = record number; S = sex; A = age; Ischaemia = ischaemic ST episodes in leads 0,1,2; HR = heart-rate related ST episodes in leads 0,1,2; ST/I = combined ST change episodes and combined ischaemic ST episodes; A/C = ST shifts due to axis shifts in leads 0,1,2 (left), and due to conduction changes in leads 0,1,2 (right); diagnosis: 2-VCAD = 2-vessel coronary artery disease; 3-VCAD = 3-vessel coronary artery disease; AAA = abdominal aortic aneurysm; AAMI = anterior acute myocardial infarction; A = angina; AF = atrial fibrillation; ASTH = asthma; BPH = benign prostatic hypertrophy; CAD = coronary artery disease; CHF = congestive heart failure; COPD = chronic obstructive pulmonary disease; CRF = chronic renal failure; CVA = stroke; DCM = dilated cardiomyopathy; EA = effort angina; HC = hypercholesterolaemia; HL = hyperlipidaemia; HTN = hypertension; IDDM = insulin-dependent diabetes mellitus; ILMI = inferolateral myocardial infarction; LBBB = left bundle branch block; LHTN = labile hypertension; LIMA-LADCA = left internal mammary artery graft to left anterior descending coronary artery; LVDD = left ventricular diastolic dysfunction; LVF = left ventricular failure; LVH = left ventricular hypertrophy; MA = mixed angina; MHTN = mild hypertension; MI = myocardial infarction; MS = mitral stenosis; MVP = mitral valve prolapse; NoCAD = no coronary artery disease; NOHCM = non obstructive hypertrophic cardiomyopathy; OA = osteoarthritis; OHCM = obstructive hypertrophic cardiomyopathy; PAI = peripheral arterial insufficiency; PCABG = previous coronary artery bypass grafting; PCVAx4 = previous strokes x4; PFO = patent foramen ovale; PFPB = previous femoral-popliteal bypass; Pgn = pregnant; PMA = Prinzmetal's angina; PMI = pre-previous myocardial infarction; PPT = palpitations; PRT = prostatitis; PSMI = previous subendocardial myocardial infarction; PTURP = -previous transurethral resection of prostate; RA = resting angina; SS = spinal stenosis; SYE = syncopal episodes; SY = syncope; SyX = syndrome X; SZ = seizure disorder; TIA = transient ischaemic attack; UA = unstable angina; WPW = Wolf-Parkinson-White syndrome

experts. There are 68 two-channel recordings and 18 three-channel recordings. The records vary in duration from approximately 19 h to 26 h. Table 3 summarises the content of the records with diagnoses and numbers of annotated ST events according to protocol A. The subjects were 46 men, aged from 44 to 85 years, and 29 women, aged from 23 to 87 years, for five subjects, sex and age data are not available. Each record contains significant ST events of some type. Transient ST segment episodes were counted in each ECG lead separately, as annotated, and in the sense of combined ST annotation streams. Column ST/I in Table 3 summarises the numbers of *combined ST change episodes* and *combined ischaemic ST episodes*. Combined ST change episodes are those obtained by merging the ST episode annotations of ischaemic ST episodes and of heart-rate related ST episodes from the simultaneous leads into one single ST annotation stream, regardless of the type of ST episode, i.e. a combined ST change episode occurs if an episode of any type occurs in any lead. Combined ischaemic ST episodes are those obtained by merging the ST episode annotations of ischaemic ST episodes only into one single ST annotation stream, i.e. a combined ischaemic ST episode occurs if an ischaemic ST episode occurs in any lead.

Table 4 summarises the overall numbers of annotated ST segment episodes and their durations for the annotation protocols A, B and C. The total gross database duration is 1991:50:49 (1991 h, 50 min and 49 s), and the average duration of records is 23:09:40. According to protocol A, the LTST DB contains 856 true ischaemic ST episodes in lead 0, 786 episodes in lead 1 and 153 episodes in lead 2. Combining the ischaemic and heart-rate related ST episode annotation streams from the simultaneous leads yields 1490 combined ST change episodes of total duration of 200:22:42 (average episode duration 0:08:04), whereas combining ischaemic ST episode annotation streams yields 1155 combined ischaemic ST episodes of total duration of 151:40:12 (average episode duration 0:07:53).

Table 4 Overall numbers and durations of annotated ST segment episodes in LTST DB

Protocol	Ischaemia	HR	ST	ST (h:m:s)	ST_A (h:m:s)	I	I (h:m:s)	I_A (h:m:s)
Total duration of database: 1991 h 50 min 49 s Average duration of records: 23 h 09 min 40 s								
A	856, 786, 153	278, 232, 6	1490	200:22:42	0:08:04	1155	151:40:12	0:07:53
B	543, 506, 81	132, 99, 3	908	157:11:54	0:10:23	743	122:50:06	0:09:55
C	411, 393, 53	68, 47, 1	663	136:37:44	0:12:22	571	110:24:36	0:11:36

Ischaemia = ischaemic ST episodes in leads 0,1,2; HR = heart-rate related ST episodes in leads 0,1,2; ST = combined ST change episodes; ST(h:m:s) = total duration of combined ST change episodes; ST_A(h:m:s) = duration of average combined ST change episode; I = combined ischaemic ST episodes; I(h:m:s) = total duration of combined ischaemic ST episodes; I_A(h:m:s) = duration of average combined ischaemic ST episode

Samples of the LTST DB are available*, and the entire database has been published on DVD-ROMs and CD-ROMs†. The database also includes a subset of utility files containing diagnostic and morphology feature-vector time series used during annotating. These files are in text format and include ST level, ST reference and ST deviation functions of the records, and time series of ST segment and QRS complex KLT feature vectors. The SEMIA annotation tool, version 3.0.1, that permits the viewing and examination of feature-vector time series and database annotations is a part of the database and is available‡.

4 Discussion

Transient myocardial ischaemia is an important clinical problem, and it has been demonstrated that much of it may be asymptomatic, but detectable using the ECG. AECG recording therefore has a role in the diagnosis and follow-up of at-risk patients. Automated systems are needed accurately to quantitate ischaemia in AECG recordings. However, such systems are difficult to design, because of the many non-ischaemic ST events and artifacts that are present in real-world ECG data. There is also a need for tools to evaluate the performance of devices that claim to detect transient ischaemia. The long-term ST database described in this paper will provide a critically important research resource for algorithm developers and will also make it possible to evaluate detector performance in a reproducible manner.

The development of this database was complex, resource intensive, time consuming and painstaking. The project benefited from the expertise, resources and experience of the research groups and drew upon experiences obtained during the development of the previous MIT-BIH, AHA and ESC databases. The semi-automatic interactive graphic tools were critical to the success of the project. They supported paperless work and facilitated international co-operation via the Internet. Reviewing and correcting the annotations after their automatic derivation, instead of fully manually annotating, proved to be much faster and more convenient for human experts.

It is important to emphasise that the LTST DB is not intended as a replacement for the ESC database§, or MIT-BIH‖ or AHA databases¶. Its goals are different. The LTST DB fills a gap in the scope of previously published databases. The MIT-BIH# and AHA☆ databases are intended for evaluating arrhythmia and ventricular arrhythmia detectors. The ESC DB** contains 2 h ambulatory records and is annotated beat-by-beat in terms of QRS onset, beat type, arrhythmias and ST segment and T-wave changes. It is intended for evaluating detectors of transient ST segment and T-wave changes, as well as for testing QRS detectors in the presence of ST-T abnormalities.

The LTST DB contains long-term ambulatory records and ST segment measurements obtained on average waveforms. What we hoped to accomplish was to represent better the wide variety of real-world data, including many examples of ischaemic and mixtures of non-ischaemic ST events. The LTST DB will support the development and evaluation of the performance of algorithms to detect transient ischaemic and non-ischaemic ST segment changes. It will also support researchers studying lengthy examples of quasi-periodic and other temporal patterns of ST change and enable basic studies in the dynamics of mechanisms responsible for ischaemia.

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*http://www.physionet.org/physiobank/database/ltstdb/

†Long-term ST database: available from: Long-Term ST Database Distribution, Faculty of Computer & Information Science, Laboratory of Biomedical Computer Systems & Imaging, Tržaška 25, 1000 Ljubljana, Slovenia (contact: Professor Franc Jager, e-mail: franc.jager@fri.uni-lj.si)

‡http://www.physionet.org/physiobank/database/ltstdb/semia

§European ST-T database: available from: European ST-T Database Distribution, CNR Institute of Clinical Physiology, via Moruzzi 1, 56124 Pisa, Italy (contact: Dr Alessandro Taddei, e-mail: taddei@ifc.cnr.it)

‖MIT-BIH arrhythmia database: available from: MIT-BIH Database Distribution, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room E25-505A, Cambridge, MA 02139, USA (refer to: http://ecg.mit.edu/)

¶AHA database distributor: Emergency Care Research Institute, 5200 Butler Pike, Plymouth Meeting, PA 19462, USA (contact: Ms Hedda Shupack, e-mail: hshupack@ecri.org)

#Sample records are available on http://www.physionet.org/physiobank/database/mitdb/

☆http://www.healthcare.ecri.org

**Sample records are available on http://www.physionet.org/physiobank/database/edb/

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