Ambulatory ST segment monitoring

Problems, pitfalls, solutions, and clinical application

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SUMMARY The introduction of frequency modulated recording systems for ambulatory electrocardiographic monitoring (Oxford Medilog mark 2 and Cardiodyne cassette recorders) prompted comparison with a conventional direct recording type of recorder (Oxford Medilog mark 1). The recordings obtained by the frequency modulated recorders were very much superior to those obtained by the direct recording type of recorder. The direct recording suffered from poor low frequency response, phase shift, and cable motions artefacts. Correction of these problems with careful attention to electrode application enabled stable graphs to be obtained over 24 hours. The clinical applications were explored by comparing the results of exercise tests with a computer assisted system with frequency modulated ambulatory monitoring in 30 patients. A range of ST deviations from pure ST depressions throughout 24 hours, pure ST elevation, and a combination of ST elevation and depression were seen, suggesting a spectrum of changes hitherto unsuspected in these patients. Painless ST changes were approximately twice as common as those associated with pain. These findings indicate a valuable role for ST segment monitoring in ischaemic heart disease, particularly with the availability of high fidelity modulated tracings which do not distort ST segments.

Ambulatory monitoring of the electrocardiogram for the detection and quantification of arrhythmias has become an accepted and widely used diagnostic technique.¹⁻³ High quality recordings can readily be obtained from praecordial electrodes because the shape and temporal relations of the QRS complex are the most important features for arrhythmia analysis. This means that narrow band-width recordings can be safely employed to eliminate artefact and provide a stable baseline. However, narrow band-widths impose limitations on the use of ambulatory tape recordings to monitor ST segment changes which may be significant of myocardial ischaemia, because these electrical events essentially have a low frequency, and the cut-off so essential for stabilising the baseline produces considerable ST distortion. Nevertheless, some workers have used standard direct recording ambulatory tape recorders to detect ST segment shifts, though most have been cautious in interpreting the results in a quantitative fashion.⁴⁻¹⁰ The introduction of frequency modulated (FM) recording systems should go a long way towards solving these problems, but

the dimensions of artefactual ST alterations and the precision and reproducibility of different commercially available systems have not yet been reported. We have conducted such an investigation and report the results here.

Materials and methods

This investigation was conducted in three parts:

(1) A detailed examination of the electrocardiographic electrode system to identify and correct possible sources of artefact. After considerable experimentation it was recognised that artefacts arose from the skin electrode interface, the movement of loose cables, and at the recorder cable junction. Artefacts arising at the skin electrode interface could be related to the method of skin preparation, muscle movements, electrode jelly stability, and electrode adhesion.

(2) Three tape recorders commonly used for arrhythmia detection were evaluated for detection of ST segment changes:

(a) *Oxford Medilog mark 1* direct recording at 1/60 real time continuously.*

* Manufactured by Oxford Medical Systems, Abingdon, Oxon.

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- (b) *Oxford Medilog mark 2* FM recording continuously.* This has two channels for electrocardiogram, one for time signals, and one for event marking. These can be played back at 60 times recording speed.
- (c) *Cardiocassette* FM recording at real time.† This recorder has a built in programmer which starts the recorder at preset intervals of 15 minutes to two hours and stops it after five to 30 seconds. At the shortest programme of 15-minute intervals and 30 seconds recording time, a tape lasts 18 hours. It can also be used for continuous recording for one hour and played back on any electrocardiograph at real time.

The frequency characteristics of each machine were assessed by recording 1 mV and 2 mV square wave calibration signals and playing them back into the analyser.

Each recorder was then evaluated by simultaneously recording the electrocardiogram on all three in a total of 20 patients with ischaemic changes on the electrocardiogram during exercise. The standard for comparison was an online digital computer-assisted multichannel exercise system which produced continuous computed values for ST depression/elevation and ST slope‡ (Marquette; CASE). The exercise electrocardiogram was recorded with this system as a standard. The recordings from the *Cardiocassette* were played back directly via the CASE system. The *Medilog mark 1* and *mark 2* recordings were converted into real time with suitable flutter compensation and then played back via the CASE system. Reproduction of signals at 1:1 was ensured by the initial calibration markers. The R wave amplitude was measured manually and the ST segments were computed at the J point and the ST slope at a point one-eighth of the RR interval after the J point. Any recordings with high frequency artefacts and isoelectric drift were excluded.

(3) The clinical application of the three tape recorders was assessed in relation to the exercise test. Ambulatory electrocardiograms of 30 patients with positive exercise tests and symptomatic angina were monitored using two bipolar precordial leads CM5 and CC5. The tapes were played back on an Oxford PB-4 deck into a Reynolds Medical Pathfinder electrocardiographic analyser with an ST segment plotter.§ The plotting module had a zero reference, calibration markers, and two spots which could be positioned on the most horizontal part of the PR segment (isoelectric level) and on the J point of the ST segment. The ST segment plotter

estimated the difference in amplitude between these two points, excluding artefacts and ectopic beats. The analogue output of heart rate and ST segments were fed into a linear recorder at a paper speed of 1 cm/hour of real time recording. The ST segment changes were correlated with the exercise test results and the patient diaries. Any ST depression or elevation at least 1 mm below or above the isoelectric line, the total episode lasting at least for six minutes, was defined as abnormal for the purposes of this study.

Results

Electrode sites were chosen over bony sites free of major muscle masses. The manubrium sterni, left sixth rib in the anterior axillary line, and the right sixth rib in the anterior axillary line were chosen as standard sites to give the two bipolar leads CM5 and CC5. The skin over the area was shaved if necessary and cleaned with isopropyl alcohol to remove grease. The electrode sites were then marked with a felt pen and touched with a high speed battery operated burr with an abrasive tip¶ to remove the stained epidermis. This process was entirely painless, unlike brisk rubbing with rough gauze, the method commonly used.

Various commercially available electrodes were tested for stability of the gel and adhesion characteristics. A new electrode, with nickel coated brass as the electrode material and a chloride-free gel isolated in a bubble pack until application, was found to yield stable tracings. It also used a strong non-allergenic adhesive developed for colostomy bags (Roussel Medical Ltd).

Cable movement artefacts were reduced by attaching the preamplifiers to the cables close to the electrodes and applying an elastic porous bandage around the chest to keep the electrodes, preamplifiers, and cables free from movement.

A special connection was designed to fix the cables to the recorders and prevent bending and movement at these sites. These simple measures produced a dramatic improvement in the stability of the isoelectric line (Fig. 1).

RESPONSE TO SQUARE WAVE CALIBRATION

The response to a 1 mV square wave calibration pulse was defined as adequate if it fell within the recommendations of the American Heart Association.¹¹ The *Cardiocassette* and *Oxford Medilog mark 2* recorder both produced an adequate response at 1 mV and 2 mV levels. On the other hand, the *Medilog mark 1* produced distortion of the peak of the calibration signal and artefactual depression of the baseline (Fig. 2).

¶ MS Expo Ltd, Sustanum Works, Titchfield, UK.

* Manufactured by Oxford Medical Systems, Abingdon, Oxon.

† Manufactured by Cardiodyne Inc, Cupertino, California, USA.

‡ Marquette Electronics Inc, Milwaukee, Wisconsin, USA.

§ Manufactured by Reynolds Medical Limited, Hertford.

Fig. 1 The top panel (A) shows artefacts commonly seen during ambulatory monitoring. The lower recording (B) shows elimination of artefacts by measures described in text.

R WAVE AMPLITUDE

This was carefully measured particularly because of the renewed interest in R wave amplitude in ischaemic heart disease.¹² Measurements made from recordings using the Cardiocassette and the Medilog mark 2 were consistently within 5 per cent of the standard. The Medilog mark 1 consistently underestimated R wave amplitude by between 10 and 27 per cent (mean $\pm$ SEM $19.1 \pm 1.0\%$) (Table 1).

ST SEGMENT CHANGES

The maximal ST segment changes measured with the three recorders were compared with the standard. In 19 out of 20 recordings using the Cardiocassette the measurement was within 0.5 mm of the standard, in 15 it was within 0.2 mm, and in two recordings it was identical with the standard. One recording could not be analysed because of high frequency artefacts.

The Oxford Medilog mark 2 produced recordings in which maximal ST segment change was within 0.5 mm of the standard in 18 and within 0.2 mm in four. Two recordings could not be analysed because of high noise levels.

The Oxford Medilog mark 1 produced six recordings in which measurements were within 0.5 mm of the standard and two recordings within

0.2 mm of the standard. In seven, differences were greater than this, the maximum being 1.2 mm. Five recordings could not be analysed because of high frequency artefacts.

ST SLOPE

The ST slope was within 0.5 mV/s of the standard in 12 out of 20 Cardiocassette recordings and within 1.0 mV/s in seven. The Medilog mark 2 produced 10 recordings in which ST slope was within 0.5 mV/s of the standard, and in the rest ST slope was within 1.0 mV/s.

Measurements of ST slope from recordings obtained using the Medilog mark 1 differed from the standard by more than 1.0 mV/s in all recordings. In six cases slopes which were negative were read as positive and in three slopes which were positive were read as negative.

Generally, the tracings obtained from the Cardiocassette were the clearest. Initially the noisiest tracings were those produced by the Medilog mark 2; this was attributed to the replay system and was later corrected. Mark 1 recordings were noise free. Some of the common artefacts seen with mark 1 recordings are shown in Fig. 3.

The clinical applications of an ambulatory

Fig. 2 Response of Medilog mark 1 DR (lower panels) and mark 2 FM recorders (upper panels) to 1 mV and 2 mV square wave calibration signals. Distortion of the deflection and the baseline is always present in mark 1 recordings.

Table 1 Comparison of exercise tests (20 patients)

	Cardio- cassette	Medilog mark 2	Medilog mark 1
R wave amplitude	19	18	0*
(5%)			
Peak ST change	19	18	6
(0.5 mm)			
Peak ST change	15	4	2
(0.2 mm)			
ST slope at peak exercise	12	10	0†
(0.5 mV/s)			
ST slope at peak exercise	7	8	0†
(1 mV/s)			
Artefacts	1	2	5
Noise level	Nil	+	Nil

* Constant underestimation by 10 per cent.

† All values beyond 1 mV/s.

Figures within parentheses indicate the acceptable variation from the standard.

recording system are to document changes which are not detectable in resting or exercise electrocardiograms and to collect additional information about changes during day and night. Table 2 shows the frequency of ST changes and of episodes

Table 2 Pain and ST changes

Number of patients monitored	30
Total duration of tapes	612 hours
Exercise test positive	30
Total episodes of pain	61
ST change over 1 mm	194
ST change over 2 mm	112
ST change with normal heart rate	21

Fig. 3 Some of the artefacts commonly seen in ambulatory monitoring. The top panel shows a stable resting electrocardiogram. In the second panel an increase in heart rate has produced an increase in the amplitude of T wave and an artefactual depression of the TP segment caused by phase shift. Panels 3 and 4 show artefacts caused by cable-recorder junction movements, and panel 5 those resulting from the electrode jelly drying up.

of chest pain. The following case reports illustrate the value of ambulatory ST segment monitoring.

Case 1 (Fig. 4)

A 59-year-old male office worker complained of squeezing pain in the neck brought on by exertion and relieved by rest. Treadmill exercise testing produced identical pain accompanied by 4.1 mm ST depression in lead CM5. An ambulatory tape recording showed many episodes of ST depression during a 24 hour period. Moreover, pain in the neck was consistently associated with ST segment depression of 4.0 mm and an increase in heart rate.

Case 2 (Fig. 5)

An electrical engineer complained of recurrent attacks of angina, usually at rest. He was able to exercise for 14 minutes before developing 2.0 mm ST depression. Ambulatory monitoring was performed as the excellent exercise tolerance did not explain the occurrence of frequent angina at rest. The patient developed pain while driving and had four episodes of ST elevation lasting more than 20 minutes each. Coronary arteriography and ²⁰¹Tl scintigraphy confirmed the presence of critical obstructive coronary artery disease, presumably associated with intermittent spasm.

Case 3 (Fig. 6 and 7)

A 47-year-old woman complained of recurrent chest pain associated with giddiness and occasional blackouts. Repeated exercise tests were normal. Ambulatory monitoring showed six episodes of ST elevation during pain, two with ventricular tachycardia. The patient was treated with verapamil 120 mg t.d.s. and became symptom free within a

Fig. 4 Case 1. 24-hour trend chart of ST segment changes in leads CM5 and CC5. The isoelectric line is marked by thin black lines at end of the recording. Only the initial episode of ST change was associated with pain in the neck.

Fig. 5 Case 2. The 24-hour trend chart shows one episode of ST depression with increased heart rate at 1500 hours and four episodes of ST elevation lasting between three and five minutes after 0630 hours. Only one episode was associated with pain.

week. Repeated ambulatory monitoring showed no episodes of ST elevation. Coronary arteriograms were normal.

Case 4 (Fig. 8)

A 53-year-old man had had severe angina for two years. His angina was mainly effort related, but recently had occurred also at rest and at night. The exercise test showed 4.0 mm ST depression at 8.0 minutes. Ambulatory monitoring showed episodes of ST depression occurring during the day and the night; on two occasions at night ST elevation preceded ST depression. Coronary arterio-

grams showed a 90 per cent stenosis of the left main stem; ventricular fibrillation occurred during the procedure but he was successfully resuscitated. A saphenous vein bypass graft operation was performed and the patient was much improved.

Case 5 (Fig. 9)

A 51-year-old woman was attending the outpatient department of the hospital for pain in the left thenar eminence. This pain was brought on by exertion and relieved by rest, but she had also had episodes of similar pain at night. The differential diagnosis before referral to the cardiac department included

Fig. 6 Case 3. A continuous tracing in a patient with Prinzmetal's angina. The ST elevation progressively increases within a very short time.

Fig. 7 Case 3. ST elevation associated with ventricular tachycardia in the same patient. Note the very rapid return to normal. An intermittent or patient-activated recorder could have missed these changes.

Fig. 8 Case 4. Conspicuous ST depression occurring repeatedly, and two episodes of ST segment elevation during the early morning. These two episodes are shown at a higher speed in the later part.

carpal tunnel syndrome, cervical spondylosis, a psychosomatic disorder, and peripheral neuropathy. She had undergone a full range of neurological investigations including myelograms, all of which were normal. Ambulatory monitoring showed episodes of ST depression of 1 mm or more, each of which was associated with pain in the thenar eminence. Exercise testing confirmed that the ST depression and thenar pain occurred at the peak exercise level. Coronary arteriograms showed total occlusion of the right coronary artery and 90 per cent stenosis of the circumflex artery, and ^{201}Tl scanning showed ischaemia. The patient refused operation.

Discussion

Ambulatory monitoring of the electrocardiogram to define ST segment changes is a practical and rewarding technique which can be of great diagnostic significance, particularly with regard to coronary spasm. It may also yield quantifiable data on the duration of periods of myocardial ischaemia. Early attempts to record these changes have met with justifiable criticism.^{13 14} The recorders used in these studies were of the direct recording type and there were problems with phase shift and poor low frequency response. Berson and Pipberger¹³ pointed out the limitations of low frequency response amplifiers and recorders and recommended the use of recorders with at least 0.05 Hz cut-off frequency. Hinkle and co-workers¹⁴ reported the results of their tests with the Holter Avionics system and emphasised that this should not be used for critical ST segment analysis. After improvement in the frequency response of this system, a number of

studies were reported using this reel-to-reel type of recorder.⁵⁻⁷

The Oxford Medilog multichannel recorder (mark 1) is widely used in Europe. It has a claimed low frequency cut-off of 0.15 Hz but there are no validation data available on its performance characteristics. Selwyn and co-authors⁹ used this system but it is doubtful if these results can be accurately quantified. The validation tests we have performed show considerable ST segment distortion, poor reproducibility of a standard 1 mV square wave, and quantitative differences from a standard reference. In contrast, the two FM recorders showed excellent reproducibility with no detectable distortion. The square wave calibrations were clean and there was no distortion of the baseline. In addition, the design of the Medilog mark 2 eliminated problems associated with recorder-cable junction movement and the calibration remained stable over a 24 hour period.

Even though the programmed recorder (Cardio-cassette) could be used to sample ST changes every 15 minutes or during symptoms, we found instances when its use would have missed significant events. For example, in case 3 there was transient ST elevation which disappeared within a minute (Fig. 6 and 7). Furthermore, there were at least six episodes of ST depression in case 5 which occurred at night while the patient was asleep and which were painless. It appears that if realtime recorders are to be used a sampling rate of at least once a minute would be necessary.

Our investigation clearly showed the need for careful attention to the electrode system whatever the quality of the tape recorder. We devoted

Fig. 9 Case 5. ST segment depression occurring during exertional pain ($\uparrow$) in the left thenar eminence and during the night also.

considerable time and effort to improve signal quality. It was found to be absolutely essential to shave the hair, clean the skin with isopropyl alcohol, abrade the skin with a high speed dental rotary burr, and use stable electrodes. The application of four electrodes took seven to 10 minutes and the time and care spent on this was always worth while. Fixing the electrodes with a porous elastic bandage (Coban) was satisfactory. However, this occasionally produced skin irritation and specially designed elasticated vests were found to be more satisfactory.

One of the disadvantages of ambulatory monitoring is the generation of large amounts of data which require automated methods for its analysis. We have used an ST segment trend system using two spots, one located on the PR segment and the other at the J-point. This system excludes artefacts and ectopic beats automatically. Our validation data were obtained by converting the signals into real time and analysing them with the CASE system; this could be done as the recordings lasted only 20 to 30 minutes each. This method is clearly impracticable for routine use and we are now exploring the possibility of developing a purpose built programable minicomputer for ST segment analysis in accelerated time.

The detection of at least two episodes of painless ST segment change for every painful episode is of importance both prognostically and therapeutically. Furthermore, the successive occurrence of ST depression and ST elevation suggests coronary artery spasm even in ambulant subjects with relatively stable angina; this interpretation is supported by the recording of such changes at night with little or no tachycardia. Accurate and reliable ambulatory FM recording of the ST segment for 24 hours or more appears to be a valuable method of examining the profile of changes in ischaemic heart disease. It does not render exercise testing superfluous, as it yields different and useful additional information.

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