

Electrode studies for the long-term ambulatory ECG

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Abstract—Noise and motion artefacts interfere with ambulatory ECG recording. In the paper the hypothesis that proper skin preparation and electrode design and placement could reduce the artefact levels is tested. The comparison of four commercial electrodes shows differences in adhesive strength and levels of skin irritation but does not indicate significant differences in the artefact levels produced by the electrodes. Four treatments are compared—no skin preparation, rubbing with alcohol, abrasion and puncturing—for their effectiveness in reducing motion artefact. Skin preparations do not reduce the motion artefact significantly, but cause much discomfort. Therefore, skin preparation is not recommended. We recorded the signal- (QRS complex) to-noise (artefact at the electrode site) ratio at 15 thoracic locations and recommend two pairs for ambulatory ECG recording. The statistical experimental design procedures used can also be adopted for comparison and testing for improvement of other electrode properties and designs.

Keywords—Adhesion, Artefact, ECG, Electrodes, Evaluation, Irritation, Location

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1 Introduction

A MAJOR problem with electrocardiographic (ECG) recording is interference from external sources such as muscle noise, 60 Hz interference and baseline drift. Further, displacement of skin and electrodes causes motion artefact. Such motion artefact very often resembles the ECG which makes automatic monitoring and recording difficult. With automated arrhythmia detectors (THAKOR *et al.*, 1984), the result is false detections and alarms.

WEBSTER (1977) reviewed the sources of electric interference in biopotential recording. These can be divided into environmental, and physiological. The environmental interference comes from: mains powerline interference; high-frequency interference from communications equipment; electrosurgical and other equipment; magnetically induced interference; and electrostatic and triboelectric interference. Physiological interference in ECG recording arises from the muscle (EMG), motion artefact owing to the displacement of recording electrodes with respect to the skin, and slow baseline drift associated with respiration. HUHTA and WEBSTER (1974) described many techniques to reduce the environmental interference by using good recording techniques and instrumentation. The physiological artefacts are more difficult to deal with. Experimental work by THAKOR (1978) shows that the motion artefact can be reduced and larger QRS amplitude can be obtained by selective placement of electrodes. MASON and LIKAR (1966) identified the thoracic equivalent of the electrode locations used for conventional 12-lead ECG. HILL and DOLAN (1976) reviewed various thoracic locations presented in the literature. The MX lead dramatically reduces muscle artefact (GEDDES *et al.*, 1960).

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Motion artefact can be reduced by skin preparation. It is assumed that the epidermis is the source of skin potential and motion artefact (FOWLES, 1974). The epidermis consists of an external stratum lucidum, assumed to be the barrier layer, the granular layer and the dermis. The epidermis shows a continuous gradation of cells ranging from the dead outer layer to live dermis. In the upper μm , or so, there exists a layer that acts as a semipermeable membrane, preventing external fluids from entering the body tissue. This gives rise to concentration gradients and electrochemical potentials. Further, the sweat glands traverse the epidermis, giving rise to the sudoripic potential. ODMAN (1980) showed that the motion artefact is due to the deformation of the epidermis; this results in a change in the skin potential but very little change in the skin resistance.

BELL *et al.* (1939) first described abrasion with fine glass-paper for reducing skin resistance. SHACKEL (1959) showed that the skin potential disappears if the skin is drilled with a fine dental burr. Subsequently, many researchers have investigated this effect. TAM and WEBSTER (1977) showed that abrading through the barrier layer with a fine sandpaper eliminates the electrode-skin motion artefact. BURBANK and WEBSTER (1978) quantified this abrasion by developing a skin puncture tool formed from a 0.5 mm protruding blood lancet held in an X-acto knife. Skin stripping with adhesive tape is traditionally used for precise removal of the epidermis in psychophysiological measurements. An alcohol swab is used as a cleanser if applied mildly, but abrades the skin if applied vigorously.

BURBANK and WEBSTER (1978) also reported the disappearance of the skin potential. Normal skin has a high resistance loading the generator of skin potential. When the skin is punctured, the skin potential generator becomes short circuited by the low resistance of the puncture. Similarly, the source of skin potential gradually reappears as the skin

grows again. TAM and WEBSTER (1977) recorded reappearance of the skin potential over 24 h, but did not provide measurements over extended periods.

In this paper, we present the results of the experimental investigations to compare:

- (i) four skin preparation techniques—none (control), rubbing with alcohol, abrasion and puncturing
- (ii) electrode design and performance of several commercial electrodes
- (iii) 15 thoracic locations to identify the pairs that give the best signal-to-noise ratio.

2 Methods

2.1 Experimental technique

For the comparative study of the skin preparations and the electrodes, we selected four locations in the left midaxillary area (Fig. 1a) to take advantage of the fairly uniform anatomical surface. We randomised the exact location of the treatment (skin preparation or the electrode type) to eliminate the bias contributed by any one location. We replicated the tests on eight subjects to account for variability among the subjects. To identify the best thoracic locations, we selected 15 thoracic locations (Fig. 1b) and replicated the tests on eight subjects of varying ages and both sexes.

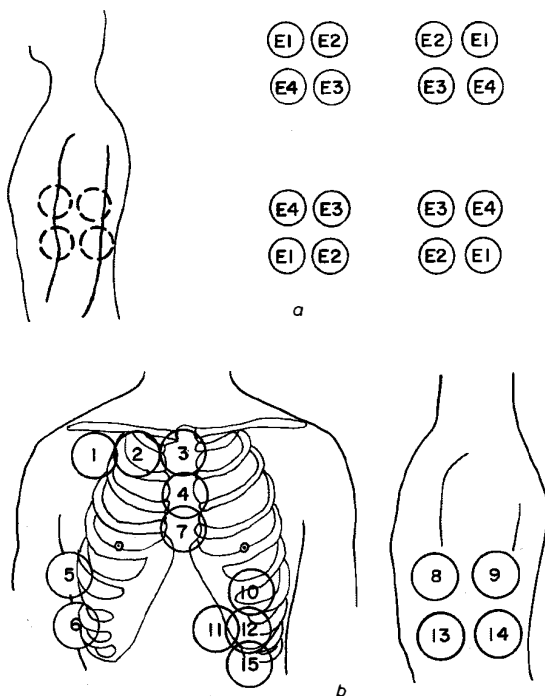


Fig. 1 (a) Location of four treatment sites and randomisation of treatments over the four sites, (b) 15 thoracic locations of placement of electrodes

The subjects exercised on a treadmill running at 2 miles/h. We recorded the ECG for 30 consecutive heart-beats, and measured the amplitude of each QRS complex and the largest artefact spike between each pair of beats. The tests were repeated at 1, 12, 24, 36, 48, 60 and 72 h. In the experiments conducted to determine the best thoracic locations, the subjects carried out a standard exercise protocol comprising bending, lifting a 5 kg weight and jogging on a treadmill for 30 s. The reference site, whenever needed, was

an electrode placed over a freshly abraded site made up by the left midclavicular line and the second rib.

2.2 Analysis of data

The statistical model for the purpose of comparing various treatments is

$$Y(ijk) = R(i) + P(j) + T(k) + RT(ik) + PT(jk) + RP(ij) + RPT(ijk) + E \quad (1)$$

where Y is the overall artefact measured, R is the contribution from the treatment, P is the possible contribution of the placement, T is the contribution from the time of measurement, the remaining are error terms from possible interactions (RT , PT , RP , and RPT), and E is the residual effect. The data were analysed using the analysis of variance technique (Box *et al.*, 1978). The analysis of variance table calculates the variance values contributed by each factor, including the treatment, from which the F -ratios and the significance levels can be assessed.

Occasionally, before completion of the scheduled 72 h of tests, the electrodes fell off due to poor adhesion or had to be removed as they caused excessive irritation. To account for missing data the corresponding measurement with a penalty number equivalent to the largest artefact voltage recorded for that experiment was substituted.

From the measurement of the QRS amplitude and the artefact voltage we derived a signal-to-noise ratio (SNR) for the electrode pair $i-j$ as follows:

$$SNR = \frac{\text{QRS amplitude between } i-j}{(\text{noise at } i) + (\text{noise at } j)} \quad (2)$$

3 Results

3.1 Skin preparations

Fig. 2 shows the plot of the artefact voltages recorded at seven different times for the four treatments. Fig. 2a shows

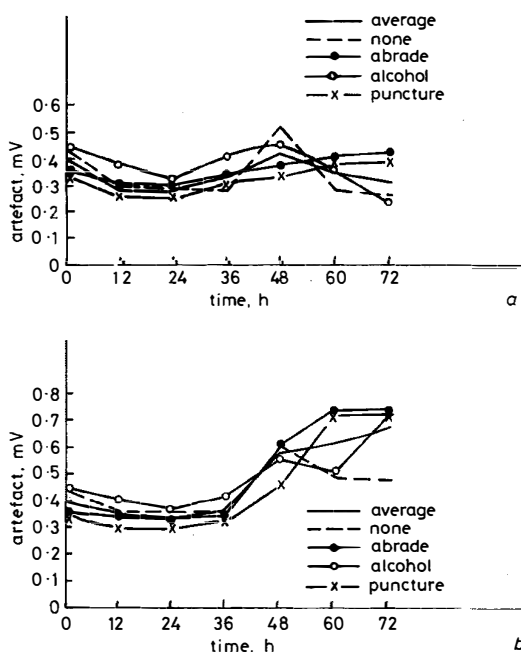


Fig. 2 Plots of motion artefact levels for four skin preparations (a) without penalty, (b) with penalty for skin irritation

the trend for true data. We introduce a figure of merit by assigning some penalty to an electrode that causes irritation (Fig. 2b). The artefact levels were observed to be higher for the first measurement and then to decline somewhat for the first 24 h and then increase slightly for the subsequent measurements. We do not see a significant increase in artefact level, as might have been expected, after the effect of the skin preparation wears off and as skin grows again at the site. But after assigning the penalties for causing irritation, the artefact levels show a notable increase after 48 h. Table 1 compares the artefact voltages for the four treatments, with and without the penalty, averaged over the entire 72 h test span. Although, the artefact levels with puncturing (E4) are the lowest, the difference does not appear to be significant. To confirm this, analysis of variance was performed to obtain the significance levels to test a null hypothesis (Box *et al.*, 1978). The null hypothesis states that there is no difference between various treatments. The significance levels in Table 2 are a measure of whether the differences observed between various treatments could have occurred by chance alone. A significance level of 0.0000 indicates that there was very small probability that such data could have been obtained due to chance experimental error. Therefore, the

Table 1. Mean artefact levels (mV) for four skin preparations

Treatment	Without penalty	With penalty
None	0.355	0.441
Abrasion	0.354	0.497
Alcohol	0.394	0.488
Puncture	0.318	0.459

Table 2. Significance levels for skin preparation tests (R, skin preparation; P, electrode position; T, time)

Source	Degrees of freedom	F-ratio	Significance level
$\frac{R}{E}$	$\frac{3}{96}$	$\frac{3.82}{4.75} = 0.8$	0.4943
$\frac{P}{E}$	$\frac{3}{96}$	$\frac{46.4}{4.75} = 9.77$	0.0000
$\frac{T}{E}$	$\frac{6}{96}$	$\frac{64.62}{4.75} = 13.61$	0.0000

data in Table 2 discredit a null hypothesis that there is no difference between various Ps and Ts. In other words, the results did vary over location and time, and we were vindicated in our caution in randomising the experimental trials. On the other hand, a high significance level of 0.49 indicates that there is a very high probability that the measured difference between various skin preparations was a chance error. In other words there was not a significant difference between various skin preparations.

3.2 Electrode design

We compared four commercially available disposable foam electrodes for their performance in ambulatory ECG recording. We selected a representative set of four disposable foam Ag-AgCl electrodes for our test:

- (a) type 3510 from NDM Corp., Dayton, OH
- (b) type 14240 from Hewlett Packard, Waltham, MA
- (c) type 2256 from 3M Co., Minneapolis, MN
- (d) type 1001 from Sentry Medical Products, Santa Ana, CA.

Table 3 shows the lifetimes of various electrodes. Although the tests could have lasted for up to a maximum of 72 h, often the electrodes had to be removed due to excessive irritation or failure to adhere. This resulted in an average duration of use of 55 h. Similar averages were calculated for onset of irritation and failure of adhesion. There were more cases of failure to adhere (13 cases) as compared with irritation (5 cases). The NDM and the HP electrodes failed sooner due to poor adhesion, while the NDM and the Sentry electrodes caused the irritation to begin sooner. Fig. 3 shows the plot of artefact voltage recorded at various times for the four electrode types. Again, we are faced with the missing data when the electrodes fell off before the test ended, or were removed due to irritation. Fig. 3a shows the artefact voltages without the penalty for falling off or causing irritation. But these data do not indicate what the artefact would have been had the electrodes stayed in place. Therefore, the presentation in Fig. 3a tends to 'forgive' the missing data. Alternatively Fig. 3b presents a figure of merit for the same data with an arbitrarily assigned penalty. As we are studying the electrode design, both falling off electrodes and the irritation they cause are indicators of their poor performance. Therefore, we penalised all the missing recordings by inserting the highest recorded artefact potential of 1.53 mV. In general, the artefact voltages decrease the longer the electrodes are kept

Table 3. Useful lifetime of four electrode types (The data indicate number of hours the electrodes were used and the cause of their failure: I, irritation; A, adhesion; N, no failure but end of test)

Subject	NDM 3510	HP 14240	3M 2256	Sentry 1001	Mean
1	54 (A)	66 (A)	54 (I)	42 (I)	54
2	54 (I)	6 (A)	66 (A)	42 (A)	42
3	72 (N)	54 (A)	72 (N)	72 (N)	67.5
4	18 (A)	72 (N)	72 (N)	72 (N)	58.5
5	72 (N)	72 (N)	72 (N)	72 (N)	72
6	42 (I)	42 (A)	72 (N)	54 (I)	52.5
7	6 (A)	18 (A)	30 (A)	66 (A)	30
8	72 (N)	30 (A)	72 (N)	72 (N)	61.5
Average use	49	45	64	61.5	55
Onset of irritation	62.5	72	69	64	67
Failure of adhesion	49	45	65	66	56

Note: We calculate averages as follows:

Average use = hours of use for all subjects/number of subjects

onset of irritation = (all I + all N)/number of cases

failure of adhesion = (all A + all N)/number of cases

in place. But with a penalty assigned for falling off or causing irritation, the artefact voltage increased sharply after 48 h. Tables 4 and 5 compare the performances of the four electrode types. Without any penalty for electrodes falling off or causing irritation, the NDM electrode gives the lowest

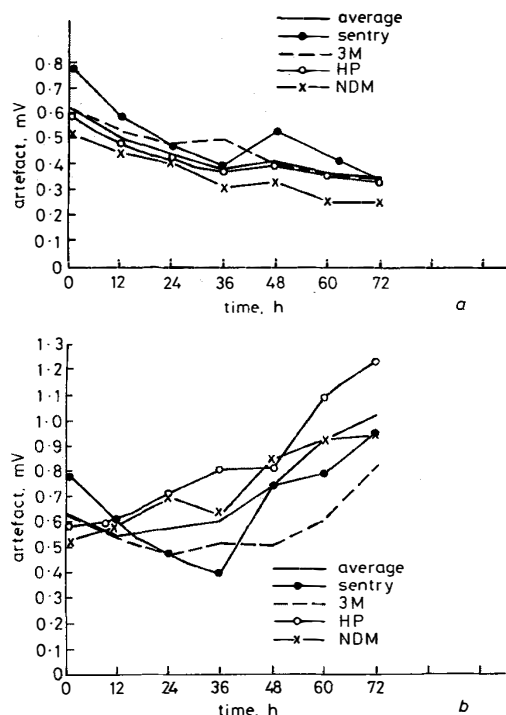


Fig. 3 Plots of motion artefact levels for four electrode types (a) without penalty, (b) with penalty for electrode falling off and skin irritation

Table 4. Mean artefact levels (mV) for four electrode types

Type	Without penalty	With penalty
NDM 3510	0.389	0.756
HP 14240	0.443	0.851
3M 2256	0.465	0.598
Sentry 1001	0.525	0.686

Table 6. QRS amplitude (mV) for various electrode pairs

Electrode pairs	7	8	9	10	11	12	13	14	15
1	2.16	2.33	19.5	2.79	2.31	2.60	2.68	2.02	2.31
2	2.16	2.43	2.03	3.09	2.31	2.70	2.61	2.13	2.40
3	2.05	2.51	2.23	3.10	2.27	2.71	2.23	2.43	2.42
4	1.83	2.97	2.61	2.95	2.39	2.77	2.95	2.67	2.64
5	2.71	1.92	1.37	2.46	1.72	1.97	1.92	1.47	1.64
6	2.58	1.56	1.20	2.35	1.80	1.93	1.70	1.23	1.57

Table 7. SNR value for various electrode pairs

Electrode pairs	7	8	9	10	11	12	13	14	15
1	2.21	2.28	1.85	2.73	2.33	2.62	2.65	1.92	2.21
2	2.40	2.51	2.08	3.26	2.49	2.95	2.78	2.18	2.47
3	2.43	2.93	2.51	3.61	2.71	3.26	2.62	2.73	2.74
4	2.29	3.51	2.99	3.48	2.90	3.40	3.52	3.06	3.04
5	3.05	2.06	1.43	2.64	1.89	2.18	2.07	1.53	1.72
6	3.05	1.77	1.32	2.67	2.09	2.27	1.87	1.35	1.73

artefact level. However, the duration of stay is smaller for the NDM electrodes, as they fall off or had to be removed due to irritation sooner than other electrodes. We reflect this aspect of poor performance with some arbitrary penalty of 1.53 mV (the highest recorded artefact value). Reflecting its better adhesive and low irritation properties, the 3M electrode performs better (with the penalty level selected). These data must be interpreted cautiously in view of the way we have treated the missing data, and assigned penalties.

Table 6 shows pair-wise measurements of the QRS amplitude between various locations. Note that all the pairs that approximate the thoracic equivalent of the lead II do have the highest QRS amplitudes. This is in general true on a sample of normal population. But the orientation of the cardiac vector may vary from individual to individual. Abnormal hearts may also present quite a different picture. Fig. 4 shows the artefact at each of the 15 locations. Table 7 shows the SNR for various electrode pairs.

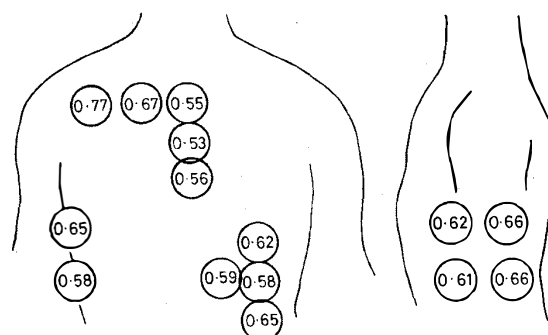


Fig. 4 Artefacts at 15 thoracic locations in millivolts

Table 5. Significance levels for electrode type tests (R, electrode type; P, position; T, time; E, residuals)

Source	Degrees of freedom	F-ratio	Significance level
R	3	67.34	0.0006
E	96	10.77	
P	3	6.8	0.6
E	96	10.77	
T	6	101.93	0.0
E	96	10.77	

4 Discussion

We have designed an arrhythmia monitor that is capable of monitoring the ECG over a period of 15 days without a battery change (THAKOR *et al.*, 1984). With the advent of large-scale integrated circuits, such as microprocessors, and low-power CMOS technology, it appears that the electronics are no longer the limiting factor in long-term monitoring; but the electrodes do limit long-term noise-free recording.

To alleviate this limitation, there were several questions to be answered. Specifically, what is the best skin preparation? In fact, is any skin preparation recommended? The electrodes from different manufacturers may perform differently. Is one brand better than another? It would be useful to have a measure of their performance, if any. The selected electrode may be placed on any of the several locations on the chest. We want to identify a few locations that give large QRS amplitude and low artefact. We studied the sources of artefacts, means of reducing them using skin preparations, the electrode designs and placement on the chest, and came to the following conclusions.

4.1 Skin preparation

On comparing abrasion, puncturing, and alcohol rub with no skin preparation, we found no significant reduction in the noise recorded in the ambulatory ECG. Possibly our skin preparation was not complete enough; but any skin preparation (more strokes of abrasion or more punctures) would have caused severe patient discomfort and possibly severe skin irritation. Also, the skin preparation does not eliminate the noise contributed by the EMG. In view of the insignificant improvement in performance and much discomfort, we do not recommend any skin preparation for ambulatory ECG recording.

4.2 Type of electrode

From our subject population we observed that the NDM and the Sentry electrodes were more prone to cause irritation. The NDM and the HP electrodes fell off most frequently. The artefact levels recorded without assigning the penalty for falling off or causing skin irritation were not significantly different for the four electrode types, although the NDM electrode had the lowest mean artefact. In the evaluation of electrodes, adhesion and irritation are as important as the artefact level. We chose to assign a penalty level of 1.53 mV, the highest artefact level recorded. These allowed us to form a figure of merit to compare measured (artefact level) as well as observed data (falling off and irritation). With this figure of merit data, we found that the 3M electrode performed slightly better than the others. These data must be observed with caution because

- (i) although assigning a penalty is necessary, it is not clear as to how large it should be
- (ii) not assigning a penalty may ignore some vital failures such as poor adhesion and gel irritation.

4.3 Variation over time

We observed artefact levels and electrode performance up to a period of 72 h. Motion artefact is highest soon after the electrodes are applied (Fig. 3a). The artefact level falls gradually with time. We believe this is due to the gel soaking into the skin, which provides a better ionic flow. We did not observe any cases of gel dilution with external water or evaporation as long as the adhesive was intact. The electrode failure came about due to the electrode mechanically decoupling itself from the skin. Another cause was a high level of irritation that made keeping the electrodes in place

undesirable. The figure of merit for the electrode performance shows a high value in the very beginning, stability for the next 48 h, followed by a rapid rise (Figs. 2b and 3b). The limit to the practical duration of use of the presently available commercial electrodes appears to be 48 h. There is quite a wide variation with patient type as to how long electrodes will adhere or how soon they will start irritating. For ambulatory monitoring, we recommend their use for not more than two days.

4.4 Electrode placement

The electrode placement on the sternum causes the lowest artefact. The highest level of QRS amplitude occurs for the thoracic equivalent of lead II configuration. A few lead pairs such as 3–10, 4–13, 4–8 and 4–10 have distinctly high SNR. These all include locations 3 and 4 which are places with very low noise. At the same time, some pairs such as 5–9 and 6–14 have low SNR due to a low value of QRS amplitude. Therefore, both value of noise at a location and its contribution to the QRS amplitude play an important role. In fact, on comparing the range of the artefact voltages in Fig. 5 and the QRS amplitude pairs in Table 6, we observe that the latter has a greater effect on the SNR calculations. This is reflected in the fact that the best pairs are placed over the thoracic equivalent of the Einthoven lead II. From the calculations of the SNR for 15 thoracic locations we recommend the following lead pairs.

- (a) Manubrium—left midclavicular/7th rib
- (b) Midsternum—left axillary/9th rib

We recommend that these pairs be alternated for long-term monitoring to allow the earlier electrode sites to recover from soreness or any discomfort experienced by keeping the electrodes attached at the same place for a long duration.

4.5 Limitations

Finally, some limitations of the study must be pointed out. It may be argued that the subject population is small. But we followed a statistical experimental design procedure that includes various randomisation techniques as suggested by Box *et al.* (1978) which give statistically significant results with small populations. Conclusions regarding the skin preparation and choice of electrodes depend on methods for treating the missing data. Our choice of assigning penalties must therefore be kept in mind and the results viewed critically (although results are provided without assigning penalties). There are many commercial ECG electrodes on the market, comprising many models from various manufacturers. In this regard, our study is quite restricted, and mainly serves to illustrate the testing methodology.

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