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Reducing skin potential motion artefact by skin abrasion

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Abstract—*Artefacts arising from variations in potential across the skin pose the greatest artefact problem remaining in a well designed biopotential recording system. We examined the nature of skin potential artefacts caused by stretch deformation, often called 'motion artefacts', and the manner by which skin abrasion reduces these artefacts, using a simultaneous skin-potential and impedence-measuring device to verify a simple d.c. electrical model of the skin. We found that abrasion reduces artefacts by resistively loading the high-impedance transcutaneous potential generator within the epidermis. We devised a needle-puncture method for producing the minimum amount of skin abrasion required to eliminate stretch artefact. We found that 10 0·5-mm skin punctures reduced the artefact from 5-10 mV to less than 0·2 mV. Skin irritation and redness are absent in the majority of cases, but cause a slight reddening in some cases. In contrast, sandpaper abrasion by an inexperienced operator often results in large welts and scabbing. We recommend puncture in clinical recording where motion artefact is a problem.*

Keywords—*Motion artefact, Skin potential, Electrocardiography, Electroencephalography, Electrodes*

1 Introduction

ELIMINATING artefact in biopotential recording has become more important with the increased use of intensive-care patient monitors and e.c.g. recording during exercise. Artefacts can arise from many sources in the recording or monitoring system. HUHTA and WEBSTER (1973) analysed sources and methods for reducing interference originating in the biopotential amplifier and lead system. KAHN and GREATBATCH (1974) and PLONSEY (1969) explored sources of artefact related to the electrode metal-to-solution interface. TAM and WEBSTER (1977) demonstrated the relative immunity to this type of artefact displayed by modern paste-filled recessed Ag–AgCl electrodes compared with the older plate-type electrodes.

1.1 *Skin artefact in e.c.g. and e.e.g.*

Potentials generated by the skin and e.m.g. noise are the greatest sources of artefact remaining in well-designed recording or monitoring systems. E.M.G. artefact can often be reduced by proper electrode placement and low-pass filtering. Skin artefacts, arising from time variation of the potential from the inside to the outside of the skin, are generated by mechanically deforming the skin by stretch or pressure, and by the secretory activity of the sweat glands. From either cause, the skin potential varies with a maximum rate of around 1 mV/s. Skin potential typically varies by 15 mV during sweating and 5 mV during stretch deformation. Calculation of the signal/noise ratio for a 5 s, 5 mV stretch artefact, and typical high-pass-filter corner frequencies and signal amplitudes for the e.c.g. (0·05 Hz and 1·5 mV) and the e.e.g. (0·5 Hz and 100 μV) suggested that skin-stretch artefact is a greater problem in e.e.g. recording, in spite of the higher high-pass corner frequencyt because of the smaller amplitude of the e.e.g, signal. In practice, however, the stretch artefac. may be more severe with a moving e.c.g. subject than with an inactive e.e.g. subject. Artefact caused by sweat secretion may be a serious problem even with a motionless e.e.g. subject.

1.2 *Reducing skin artefact*

Abrasion of the skin before applying the electrode eliminates skin potential artefacts. The amount of abrasion required was not well defined before this investigation, although TAM and WEBSTER (1977) showed that a very light sandpaper abrasion was sufficient. HANISH *et al.* (1971) showed that mild rubbing with an alcohol swab did not eliminate artefact.

1.3 *Skin anatomy and skin potential*

The first thorough investigation of the skin

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potential by REIN (1928) as reported by ROTHMAN (1954) showed that isolated human skin behaved as a negatively charged (cation-permeable) membrane. KAHN and GREATBATCH (1974) imply that a liquid-junction potential (characteristic of an uncharged membrane) could explain Rein's results as well. FOWLES (1974) reviews the evidence for a cation-permeable membrane put forth by CHRISTIE and VENABLES (1971). EDELBERG (1963), examining the skin potentials obtained from many subjects using several electrolytes, was unable to show the Nernstian behaviour expected for a cation-permeable membrane. Thus, the exact nature of the epidermal potential generator is still controversial. EDELBERG (1968) presented the d.c. electrical model of the skin shown in Fig. 1*a*, which can be used to explain many of the features of electrodermal responses. R_s and E_s represent the sweat-duct resistance and potential across the sweat-duct wall. R_e and E_e are the lumped resistance and potential across the epidermal barrier-layer membrane. A change in any of the elements of the model results in a change in the skin potential. EDELBERG (1973) supported the model with more evidence. FOWLES (1974) presented a somewhat more complex version of Edelberg's model relating potentials and resistances more closely to skin anatomy.

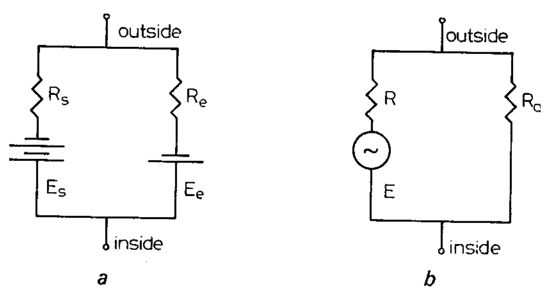

Fig. 1a Edelberg's electrical model of the skin. R_s represents the sweat-duct resistance, E_s represents the sweat-duct-wall potential, R_e and E_e represent the resistance and potential of the epidermis

b Thévenin equivalent of Edelberg's model used to predict artefact reduction

1.4 *Objective and approach*

The primary aim of this investigation was to find the least traumatic means of eliminating or reducing the skin-motion artefact. Most previous works have examined the skin-potential variations caused by sweat secretion on palmar skin. We studied the nonpalmar skin-potential variations caused by stretch deformation, using the study of stretch-deformation artefact by EDELBERG (1973), as a starting point, and Edelberg's electrical model as our paradigm for the experimental design.

2 Experimental apparatus and technique

2.1 *Artefact generation*

This procedure generated reproducible stretch-deformation artefacts on the skin of the volar aspect of the forearm. We taped a 25 mm-wide piece of 3M Micropore surgical tape on each side of the subject's extended forearm. A mass of 1 kg, when hung freely between the two pieces of tape, applied a 4·9 N force to each piece of tape to stretch a 25 mm × 25 mm square region of skin. When required, rubber cement provided an adequate adhesion to rough skin.

We modified this technique to investigate the electrical and mechanical time dependence of stretch artefacts. We attached a stretch mass of 1·5 kg to the tape at the end of a counterbalanced lever. The counterbalance was a water jug whose level could be varied at a controlled rate.

2.2 *Quantified abrasion*

A well known method for reducing skin-potential artefacts is to abrade the skin at the electrode site. SHACKEL (1959) used a dental burr to completely eliminate artefact. TAM and WEBSTER (1977) quantified artefact reduction with skin abrasion by counting the sandpaper abrasion strokes. This method required considerable skill and care to obtain reproducible results, and the technique is not readily transferable to other investigators. Another technique for removing skin layer by layer, cellophane-tape stripping, did not result in complete artefact elimination. KLIGMAN (1964) found that the amount of skin removed per stripping decreases with each repetition. Another technique, mentioned by KAHN and GREATBATCH (1974), is to puncture the skin with a needle.

We developed a controlled and quantified puncture procedure which utilised a sharp blade (BURBANK, 1976). It required no skill, was almost painless, and caused very little skin irritation. We assembled our puncture tool from an aluminium X-Acto knife handle and a Becton-Dickinson Microlance blood lancet by inserting the lancet loosely into the X-Acto knife-blade chuck. The lancet-point protrusion was easily and accurately set by tightening the knife-blade chuck while supporting the lancet end of the handle on a flat washer shim placed on a smooth tabletop. The lancet, which fell to the tabletop through the hole in the flat washer while the chuck was loose, locked in the knife chuck with a point-protrusion distance set by the washer thickness. An ordinary hardware store 4–40 flat washer set a puncture depth of 0·5 mm when used in this way. A controlled penetration depth of 0·5 mm resulted in a nearly uniform 50 μS conductance increase with each successive puncture.

2.3 *Electrolytes*

We made electrode pastes of a specified composition using a cornstarch-gel recipe (EDELBERG (1963)). Approximately 6 g of cornstarch suspended in 100 ml of cold electrolyte gelled to the proper consistency when boiled.

2.4 *Salt-bridge electrodes*

Saturated KCl paste in a porous chamber acted as a salt bridge between the 11 mm-diameter Beckman Ag-AgCl electrodes and the electrolyte paste contacting the skin. We minimised electrode d.c. offsets by storing them in a salt solution with the leads shorted.

2.5 *Simultaneous skin-potential and impedance measurement*

BURBANK (1976) described a device which measured the skin potential and impedance simultaneously. Operationally, it was similar to a computer-based instrument used by ALMASI and SCHMITT (1974).

3 Skin stretch-artefact properties

3.1 *Artefact potential-amplitude dependence on skin-stretch history*

We stretched the skin under an electrode site for a time t with a repetition period r. The resulting artefact potential amplitude A (defined as the maximum skin-potential change during skin stretch from that just before skin stretch) depended on the relaxation time $(r-t)$ before the stretch as shown in Fig. 2. The fit to an equation characteristic of a 1st-order system

$$A = A_0(1-e^{-(r-t)/\tau})$$

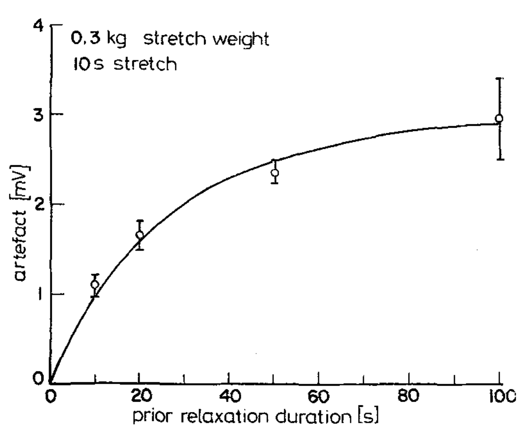

Fig. 2 Dependence of artefact amplitude on the duration of skin relaxation before stretch. Error bars indicate ±1 standard deviation for 10 trials. Solid-line interpolation is the theoretical fit of the equation described in text to data

also shown in Fig. 2, appeared to be quite good. A_0 is the maximum artefact possible, and τ is the time constant of the system. The time constant for the data in Fig. 2 is 26 s, far longer than the skin's electrical time constant (resistance × capacitance), normally about 0·1 s at low frequencies.

A mechanical explanation for this time constant must be consistent with the experimental results, described below, which showed that skin strain exhibited little time dependence. We could hypothesise a slow structural rearrangement, observable only on a microscope scale, but we have no evidence favouring this hypothesis. An electrochemical explanation based on Fick's laws of diffusion (BOCKRIS and REDDY, 1970) encounters difficulty in explaining another experimental observation described below, that the skin conductance (directly related to ionic diffusion) did not change during stretch. Thus we do not as yet have a satisfactory theory to explain the observed time constant.

3.2 *Artefact potential amplitude and strain dependence on stretch force and time*

We compared the strain-and stretch-force relationship with the artefact potential by changing the stretch force while monitoring the skin strain, potential, and impedance. We increased the stretch mass from 0–1 kg mass and then decreased it again to zero at a uniform rate of 30 g/s. The impedance showed virtually no change during this cycle. Fig. 3 shows the skin strain and artefact potential plotted against time and stretch mass. Note that although the strain was not a linear function of the stretch mass, it exhibited little time dependence or 'creep'. The artefact potential, however, showed a very pronounced time dependence as discussed above.

We expected the increase in the electrolyte contact area during the stretch deformation to decrease the electrode-site impedance by an amount proportional to the area change. A 3-5% contraction along the stretch-force normal accompanied a 5-8% expansion along the stretch-force direction. Since the strain appeared fairly constant over the measurement area, the site area increased by approximately 2·5%. Note that the percentage area change with a uniform strain does not depend on a particular electrolyte-contact-area shape, e.g. rectangular, oval, or irregular.

3.3 *Independence of skin electrical properties from NaCl electrolyte concentration*

Table 1 shows the skin potentials and impedances (measured at 10 Hz) for five subjects during skin stretch and relaxation. We applied three NaCl electrolyte pastes of 0·01, 0·1, and 1·0 N concentration at separate sites in the same stretch region. Stretch repetition of constant duration and rate generated artefacts at all three sites simultaneously. We monitored each site sequentially. The electrical behaviour for a specific site exhibited a great uniformity during the course of the experiment. There was, however, considerable variation from site to site and subject to subject. The skin potentials, artefact potentials, and impedances showed no clear trend with electrolyte concentration.

3.4 *Small change in the skin impedance during the stretch*

A significant result derived from the data in Table 1 is the small percentage change in the skin impedance during the stretch relative to the large percentage change in the skin potential. An analysis of the combined results for the three electrolytes with a *t*-test shows with 95% confidence that the mean skin impedance decreased less than 1·9% and increased less than 7·9% during the skin stretch. Such a small change in the resistive elements in Edelberg's model could not account for the 105% mean change in skin potential during skin stretch. This finding indicates that the stretch artefact results largely from potential-generator changes in Edelberg's model.

3.5 *Reduction of the artefact potential by resistive loading*

Fig. 4 shows the stepwise reduction in the artefact potential. The skin conductance increased by about 50 μS with each skin puncture. We interpreted the results using the modification of Edelberg's model shown in Fig. 1*b*. A Thévenin equivalent lumped R_e, R_s, E_e and E_s from Fig. 1*a*, into E, the equivalent skin-potential generator, and R, the equivalent intact-skin resistance. The experiment described above indicated that R was nearly constant for a particular site during the skin stretch. Since the artefact is comprised of a variation in E, we could consider the d.c. skin potential separately from the artefact potential. R_a, the resistance of the skin puncture abrasions, represented a load for E and R. The model predicted an artefact reduction from a simple voltage division across R and R_a given by the equation

$$A = A_0 R_a/(R_a + R)$$

Results from two additional experimental protocols gave credence to this model. In the first experiment, we connected an electrode over a heavily abraded skin site to an electrode over a stretch site through a variable resistor R_v. On an $x-y$ recorder, we plotted the skin potential on the x axis, and the parallel combination R_p of R and R_v. Fig. 5 shows a typical recording for a 0·3 cm^2 area stretch site. Because R was nearly constant during the stretch, the skin-potential artefact should be proportional to R_p. Within experimental variability, the data shown in Fig. 5 follow the stretch artefact reduction predicted by the model. As we decreased R_v, the artefact was attenuated by

$$R_v/(R_v + R),\ (R_a \ll R_v).$$

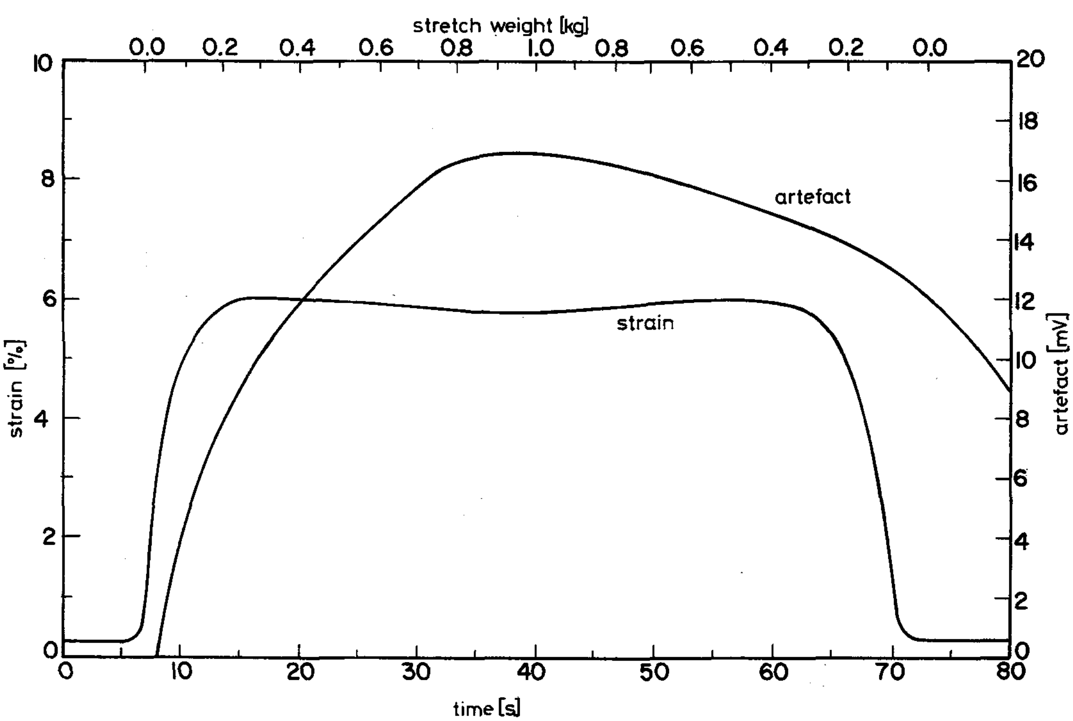

Fig. 3 Skin strain and artefact-potential dependence on time and stretch weight

As we increased R_v, the artefact returned to its initial amplitude.

The second experiment showed that artefacts produced at a stretch site could be loaded by the resistance of the intact skin beneath electrodes at sites not subject to stretch. By connecting a combination of these load electrodes of known electrode-through-skin resistance to the stretch-site electrode, we found that the artefact potential was attenuated by the factor $R_p/(R_p+R)$, where R_p is the parallel combination of the load electrode resistances. The dependence on the load resistances R_v and R_p was the same as that for R_a in the puncture abrasion experiment.

3.6 *Epidermal potential generator*

EDELBERG (1973) described the generation of potential artefacts from the fingernail bed caused by gently lifting the fingernail. This was used as key evidence in support of there being separate sources of skin potential in the sweat glands and the epidermal layer, since the nailbed has no sweat glands. To discount the possibility that the potentials recorded on the fingernail were generated elsewhere, Edelberg simultaneously recorded potentials on the fingernail and fingertip. We repeated this crucial experiment using a 2-channel version of the simultaneous skin potential and impedance-measuring device described above. The fingernail-site resistance was approximately 10 times the value of that at the site on the finger's flexor aspect. Even a thin film of electrolyte over the fingernail was sufficient to contaminate the nailbed response with 'crosstalk' from the electrodermally active fingertip. We noted a contamination by changes in both fingernail-site potential and resistance in response to nervous activity. However, with a careful technique, we avoided contamination of the nailbed response. A gentle tug on the nail generated potential artefacts of 15 mV. The site resistance remained constant. Simultaneous records from the fingertip showed variations in resistance and potential characteristic of an electrodermally active site. This experiment added support to Edelberg's contention that the epidermal layer has a potential generator separate from the sweat glands.

4 Artefact reduction in practical situations

To demonstrate the improvements in conventional e.c.g. recordings obtained by using the recommended

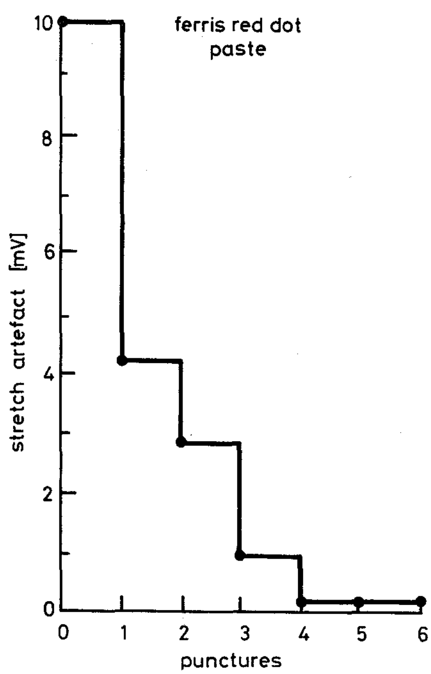

Fig. 4 Typical reduction of stretch artefact with successive 0·5-mm skin punctures

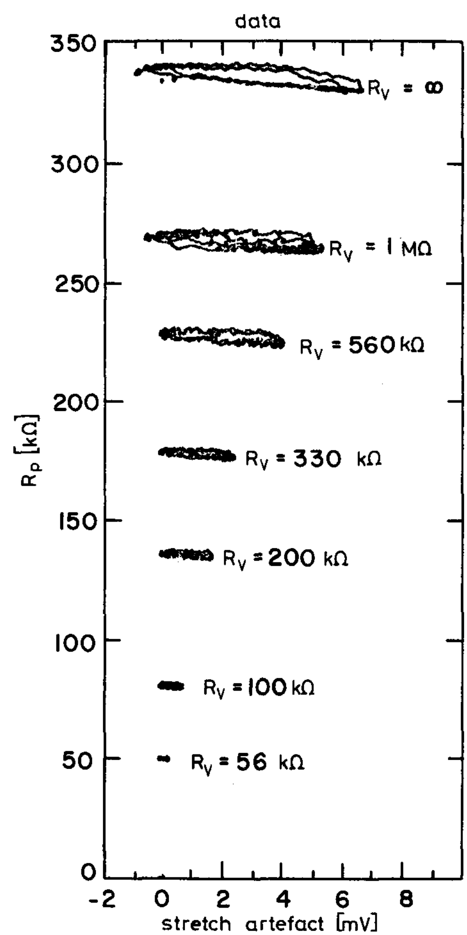

Fig. 5 Typical recording of parallel combination, R_p, of skin resistance, R, and resistive load, R_v, against skin potential during stretch

Table 1. Skin potential in mV, and skin-impedance magnitude in kΩ/cm² for relaxed skin, and changes in these values during stretch

NaCl eq/l		Skin potential mV 1·0	0·1	0·01	Skin impedance kΩ/cm² 1·0	0·1	0·01
Subject	1	− 2·4	− 6·0	−10·0	72·0	47·4	57·2
	2	−33·0	−16·0	−14·0	77·8	43·7	48·8
	3	− 0·5	−20·0	− 9·0	26·3	86·9	24·7
	4	8·0	− 2·0	−16·0	52·8	46·1	40·8
	5	−12·8	−21·2	−21·5	60·8	56·6	62·8
Mean		− 8·1	−13·0	−14·1	57·9	56·1	46·9
95% confidence		±19·5	±10·6	± 6·2	±25·0	±22·1	±18·5
80% confidence		±10·8	± 5·9	± 3·4	±13·8	±12·2	±10·2
NaCl concentration, eq/l		**Stretch artefact mV 1·0**	**0·1**	**0·01**	**Change in skin impedance kΩ/cm² 1·0**	**0·1**	**0·01**
Subject	1	14·4	14·0	14·0	0	12·0	4·1
	2	20·0	10·0	8·0	− 2·8	0·0	0·0
	3	15·5	15·6	7·5	− 2·0	5·5	0·0
	4	8·0	14·0	20·0	9·4	3·1	1·1
	5	12·0	7·2	5·5	− 3·8	− 3·0	− 2·4
Mean		14·0	12·2	11·0	0·8	3·5	0·6
95% confidence		± 5·5	± 4·3	± 7·4	± 6·7	± 7·1	± 2·9
80% confidence		± 3·0	± 2·3	±4·1	± 3·7	± 3·9	± 1·6

puncture procedure, we compared simultaneous e.c.g.s obtained from punctured (10 0·5-mm punctures) and nonpunctured sites recorded during several activities. Electrodes were placed over a punctured and nonpunctured site on the sternum and over a punctured and nonpunctured site on the lateral midline. This electrode placement minimises e.m.g. signals from underlying muscle. Hanish *et al.* (1971) have analysed electrode placement in detail. Fig. 6*a* shows normal artefact-free e.c.g.s from punctured and nonpunctured sites with the subject standing at rest. Fig. 6*b* shows e.m.g. artefact in both recordings produced by isometric contraction of the pectorals. Note that the R-wave can be clearly distinguished from the e.m.g. signals. Fig. 6*c* shows how puncture eliminated baseline shift when the subject rolled over in bed onto the electrodes. The baseline shift is caused by changes in skin potential during mechanical deformation. Fig. 6*d* shows the marked improvement in the

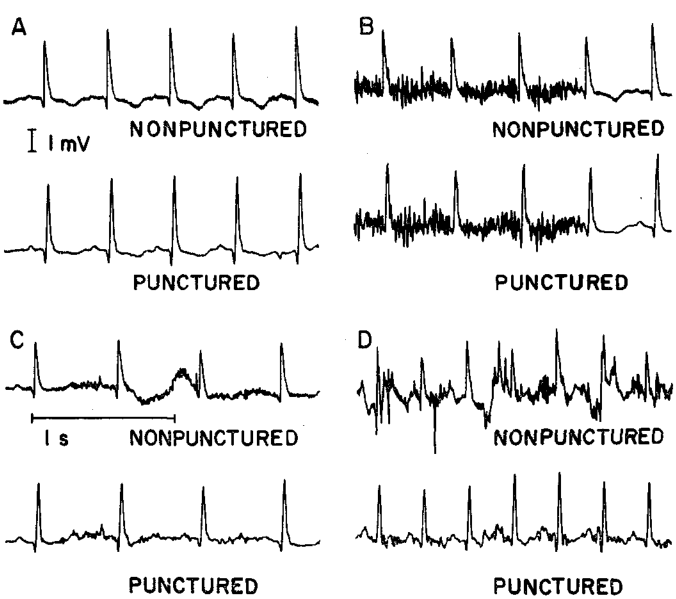

Fig. 6 Comparison of e.c.g. simultaneously from punctured (ten 0·5-mm punctures) and nonpunctured electrode sites. (A) Subject standing at rest.(B) Isometric contraction of the pectorals. (C) Rolling over in bed.(D) Runningon treadmill

treadmill e.c.g. with skin puncture. Note that skin-potential artefact from the nonpunctured sites often exceeded the amplitude of the R-wave, in sharp contrast to the e.m.g. artefact shown in Fig. 6*b*. The e.m.g. artefact remaining in the punctured-site treadmill e.c.g. was clearly of a lower amplitude than that in Fig. 6*b*. Thus we concluded that the skin-potential artefact is the greater problem in exercise e.c.g. testing, and that it can be dramatically reduced by the recommended puncture procedure.

5 Conclusions

5.1 *Epidermal potential-generator source of stretch artefact*

We have substantiated Edelberg's evidence for an epidermal skin-potential generator separate from that of the sweat gland. During stretch deformation we found no change in the skin conductance at 10 Hz. FOWLES (1974) has reviewed conclusive evidence that rapid changes in skin conductance are absent in the absence of sweat-gland secretion. Although the converse relation, that sweat-gland secretion is absent in the absence of rapid changes in skin conductance, is difficult to prove, it seems likely that this relation also holds. Thus the absence of changes in skin conductance during stretch deformation implies that sweat secretion is not involved in stretch-artefact generation.

5.2 *Artefact reduction caused by resistive loading*

We have shown that the stretch artefact generator has a high internal impedance and is resistively loaded by skin abrasion.

5.3 *Practical recommendations*

The puncture technique, requiring little skill or patience, virtually eliminates skin artefact with far less irritation than sandpaper abrasion. The procedure is so atraumatic that in the majority of cases the punctured area cannot be located for electrode positioning unless marked in some other way. Sometimes a small welt (<1 mm diameter) with skin reddening appeared at the point of puncture but always disappeared within 24 h. In contrast, sandpaper abrasion by an inexperienced operator often results in large welts and scabbing. We recommend that the puncture procedure be used in conjunction with a mild paste as discussed by TAM and WEBSTER (1977). A preliminary test indicated that 0·7 ml saturated NaCl solution mixed into a 1·5 oz tube of Johnson & Johnson First Aid Cream (0·9% NaCl in mixture by weight) makes a very nonirritating electrolyte paste compared with Beckman paste, Hewlett Packard Redux Paste, and 3M Red Dot Gel. The puncture tool used in our abrasion studies is easy to use for research but would benefit from further development before being acceptable for general use. For clinical studies the whole unit can be sterlised to avoid infection. We recommend ten 0·5 mm skin punctures before applying the electrode. It is our hope that a manufacturer will market a more convenient, sterilised, and disposable skin puncture-abrasion lancet with multiple 0·5 mm points. Thus the 10 punctures could be achieved with a single application.

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Réduction de l'artefact de mouvement potentiel de la peau au moyen du frottement cutané

Sommaire—Les artefacts issus des variations de potentiel sur la surface de la peau posent le dernier sérieux problème encore dans un système d'enregistrement du biopotentiel bien conçu. Nous avons examiné la nature des artefacts potentiels de la peau causés par la déformation due à l'extension, souvent appelés 'artefacts de mouvement', ainsi que la manière dont l'abrasion cutanée réduit ces artefacts, en utilisant un appareil mesurant à la fois le potentiel de la peau et l'impédance afin de vérifier un modèle électrique simple de la peau. Nous avons trouvé que l'abrasion réduit l'artefact en créant une charge de résistance dans le générateur de potentiel transcutané à haute impédance à l'intérieur de l'épiderme. Nous avons inventé une méthode qui utilise des piqûres d'aiguilles ce qui permet de produire le minimum d'abrasion requis pour éliminer l'artefact d'extension. Nous avons établi que 10 piqûres cutanées réduisent l'artefact de 5–10 mV à moins de 0·2 mV. L'irritation et la rougeur cutanées causées par notre méthode de piqûres disparaît en 24 h, ce qui contraste nettement avec les escarres qui sont la conséquence fréquente de la technique couramment employée d'abrasion au papier de verre. Nous recommandons donc la technique des piqûres dans les enregistrements cliniques où l'artefact de mouvement pose un problème.

Verringerung des Hautpotential-Bewegungsartifakts durch Hautabrasion

Zusammenfassung—Aus Schwankungen im Hautpotential entstehende Artifakte stellen das schwierigste Artifaktproblem dar, das auch heute noch in einem gut konstruierten Biopotential–Aufzeichnungssystem zu finden ist. Wir untersuchten durch Spannungsverformung verursachte Hautpotential-Artifakte und die Verringerung dieser Artifakte durch Hautabrasion, wobei ein Simultan-Hautpotential- und Impedanzmeßgerät zur Kontrolle eines einfachen Gleichstrom-Modells der Haut herangezogen wurde. Wir fanden, daß Hautabrasion das Artifakt reduziert, indem sie den transkutanen Potentialgenerator in der Epidermis ohmisch belastet. Wir arbeiteten eine Nadelpunktionsmethode aus, die die zur Ausschaltung von Spannungsartifakten erfoderliche Mindestabrasion herstellt. Wir fanden, daß 10 Punktionen das Artifakt von 5–10 mV auf weniger als 0·2 mV reduzierten. Durch unsere Punktion verursachte Hautreizungen und rötungen verschwanden innerhalb von 24 Stunden, im Gegensatz zu der Schorfbildung, die sich aus den herkömmlichen Abrasionsverfahren mit Sandpapier ergibt. Daher empfehlen wir Punktion in klinischen Aufzeichnungen, wo Bewegungsartifakt ein Problem ist.