Artefact Reduction With Alternative Cuff Configurations

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***Abstract*—In nerve cuff electrode recordings of neural signals, the pick-up of interfering signals can be reduced by choosing appropriate cuff configurations. In the traditionally used tripolar configuration, short circuiting of the end electrodes is expected to reduce the field inside the cuff from interfering signals. A model study suggests that moving the end electrodes toward the center of the cuff reduces the pick-up of interfering signals [9]. In this paper, these properties are studied in more detail using a rabbit model. In addition, a new cuff configuration is suggested, which has an additional set of short circuited end electrodes. The total improvement of signal-to-noise ratio in the new configuration as compared with the traditionally used tripolar configuration was 73% for muscle signals and 127% for the stimulus pulse.**

***Index Terms*—CAP, cuff configuration, cuff recordings, EMG, nerve cuff electrode, nerve signals, stimulus artefacts.**

I. Introduction

RECORDINGS with nerve cuff electrodes have made human sensory information available for use in long-term neural prostheses [1], [2]. When neural information is recorded, external sources such as muscles and electrical stimuli give rise to an interfering potential field which contaminates the recordings. The signal-to-noise (S/N) ratio in the cuff recordings is critical for the success of the prostheses and can be optimized through the choice of cuff dimensions, cuff configurations, instrumentation, and signal processing methods [3]–[14].

Because the cuff is a relatively long and narrow tube, the potential field originating from sources outside the cuff is linear with the longitudinal position inside the cuff. The traditionally applied tripolar configuration [5], where the signal is recorded between the central electrode in the cuff versus two short-circuited end-electrodes [Fig. 1(a)], gives two important properties with respect to the reduction of interfering fields of external origin:

First, by short circuiting, a terminal is created that gives the average potential of the two cuff-ends, which, because of the linearity of the potential field inside the cuff, is equal to the central electrode potential. This average potential is subtracted from the central potential, ideally yielding zero potential for the interfering signal. Second, short-circuiting of the end electrodes reduces the potential difference between the cuff-ends, thus, also reducing the field inside the cuff.

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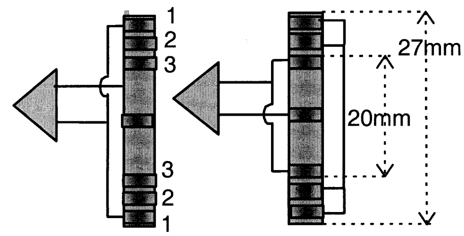

(a) (b)

Fig. 1. The cuff electrodes and the different configurations used for recording. (a) The tripolar configurations could be obtained in three different ways: t1—recording from the center electrode versus the electrode pair 1 (standard tripolar configuration); t2—the central electrode versus the electrode pair 2; and t3—the central electrode versus electrode pair 3. (b) Each of t2 and t3 could be used for recording with additional short circuiting, t2s is configuration t2 with electrode pair 1 shorted, t3s (shown in the figure) is configuration t3 with electrode pair 1 and 2 all shorted together.

In theory, short circuiting should nearly eliminate the potential gradient inside the cuff, but this has been shown not to be the case [15]. The relatively large electrode tissue interface impedance [16] at the end electrodes introduces resistance in the short circuiting path between the end electrodes and thereby limits the reduction of the internal field. In addition, any difference in the electrode tissue interface impedance at the two end electrodes leads to an average potential that differs from the potential of the central electrode, and reduces the effect of subtracting the averaged end electrode potential from the central electrode potential [15]. Therefore, the question remains: How effective is the short circuiting?

Model studies have suggested that short circuiting does indeed reduce the gradient of the interfering signals inside the cuff, but only up to a factor two [8]. Another model study suggested that additional reduction of the interfering signals can be obtained in a true tripolar configuration by moving the end electrodes of the tripole away from the cuff ends [9]. This suggests that the linearization of the field inside the cuff suffers from end effects [9].

In the present work, *in vivo* experiments were performed to study the effect of short circuiting on the field inside the cuff using bipolar recordings, and the effect on both the interfering signals and the nerve signal in the traditional tripolar configuration. The effect of moving the end electrodes away from the cuff ends on nerve signal and interfering signals are studied *in vivo* as well. An alternative tripolar configuration having additional short circuited end electrodes is suggested.

II. METHODS

A. Cuff Preparation

Six cuff electrodes with inner diameters of 2 mm and lengths of 27 mm were fabricated using the method described by Haugland [17] (Fig. 1). The cuffs had three electrodes close to each end and one center electrode [see Fig. 1(a)]. All electrodes were ring electrodes made of 25-μm-thick Pt-foil and the lead wires were made of Teflon coated stainless steel. The electrode width was 1 mm and the distance between the end electrode pair number 3 was 20 mm (Fig. 1). In addition to the electrodes inside the cuff, one electrode (1×4 mm) was mounted on the outer wall of the cuff to be used as reference for electrode impedance measurements (not shown in the figure). The cuffs were opened with a straight slit to allow for implantation around the intact nerve. The cuffs had an external flap covering the slit-opening giving an effective closure [12]. After implantation in the rabbit the cuffs were closed with three sutures. Each cuff was used in five rabbits.

B. Rabbit Preparation

Five New Zealand White rabbits were used for implantation in acute experiments on five different days. The rabbits were sedated using 1 ml midazolam (dormicum) and anaesthetised with 0,3 ml fentanyl and fluanisa (hypnorm). Every 20 min the anaesthesia was supplemented with the mentioned amounts of midazolam (dormicum) and fentanyl and fluunisa (hypnorm). In addition, a lumbar spinal block between L5 and L6 was created using 0.2 ml bupivacain, which was administrated every 60 min. Three cuffs were implanted subsequently in each hind leg around the tibial nerve, just distal to the bifurcation of the sciatic nerve (Fig. 2). Care was taken to remove potential air bubbles from the cuff. After each implantation the wound was closed with sutures and the electrode impedances were measured at 1 kHz.

One stimulation electrode (5×5 mm platinum disc 25-μm Pt-foil) was implanted on the sciatic nerve just proximal to the ramus muscularis of the sciatic nerve to evoke both compound action potentials (CAPs) from the tibial nerve and muscle signals [electromyogram (EMG)]. The distance between the proximal end of the cuff and the stimulation electrode was 25–30 mm. A needle electrode was inserted in the back of the rabbit to provide a return path for the stimulus current (Fig. 2).

The rabbits were kept warm throughout the experiments with a blanket and a heating lamp. After the experiments the rabbits were sacrificed using an injection of overdose sodium pentobarbital (Mebumal).

C. Stimulation and Data Acquisition

Supramaximal stimulation was used to activate the nerve. This was obtained by applying a current that was 50% higher than the current giving maximal response. The amplitude of the applied stimulus current was up to 5 mA and the pulse width was 100 μs. The pulse repetition rate was 4 pps.

All eight cuff wires were directly connected to a configuration board on which the different amplifier combinations were created during the experiments in order to reduce the stress on the cuff wires. The output of the configuration board was amplified 5000 times in tripolar recordings and 250 times in bipolar recordings using an Axon amplifier (Cyber Amp 380 plus preamplifiers). The amplifier was set to a bandpass filter: 300 Hz–6 kHz (second-order). In addition, a notch filter was used. Finally, the signal was sampled at 50 kHz. For each trial/configuration data were recorded for 10 ms after each stimulus pulse and each trial included ten pulses.

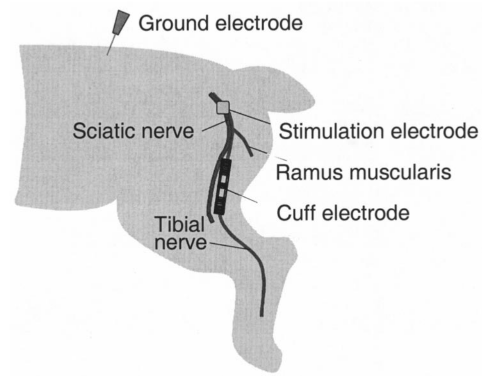

Fig. 2. The rabbit with the cuff implanted around the tibial nerve.

Signal Processing: The ten 10-ms data intervals from each trial were averaged for each configuration and S/N ratios were calculated. The S/N ratio was defined as the ratio of the CAP (peak-peak) and either the EMG (peak-peak) or the stimulus pulse (peak-peak). An improvement ratio (IR) for the different configurations relative to the S/N ratio of the standard tripole was defined as the S/N ratio of the configuration divided by the S/N ratio of the standard tripolar configuration (Fig. 1). For the bipolar recordings only noise (N) was considered and the IR was defined as the noise (peak-peak values of either the EMG or the stimulus pulse) in a standard configuration divided by the noise in the studied configuration. For each of the cuffs the average IR from the five implantations was calculated. The different configurations are described in Section II-D

$$\mathrm{IR}_{\mathrm{configuration}} = \frac{\frac{S}{N_{\mathrm{configuration}}}}{\frac{S}{N_{\mathrm{standard\_tripolar}}}}. \tag{1}$$

The significance of the results were evaluated using the Wilcoxon matched-pairs signed-ranks test [18], [19]. This nonparametric test was chosen since histograms showed that the results were not normally distributed. The null hypothesis was: H_0 = There is no difference in the S/N ratio between the two configurations being compared. The significance level of this two-sided test was 5%. Before performing the significance test, the S/N ratio of the two configurations being compared was normalized with the S/N value of the one being the reference for the comparison (the denominator for the IR value in (1). This was done to avoid results from recordings with high amplitudes to have higher weight than results with lower amplitudes.

D. Measurement Procedure

1) Effects of Short Circuiting On the Internal Cuff Field: Bipolar measurements were performed to study the effect of short circuiting on the internal cuff field. Four configurations were used.

Combination b2s: between electrodes no. 2 with short circuiting electrodes no. 1.

Combination b2: between electrodes no. 2 without short circuiting.

Combination b3s: between electrodes no. 3 with short circuiting electrodes no. 1 and no. 2.

Combination b3: between electrodes no. 3 without short circuiting.

The IR were calculated for the EMG and stimulus pulse as $\mathrm{IR_{b2/s} = N_{b2}/N_{b2s}}$ and $\mathrm{IR_{b3/s} = N_{b3}/N_{b3s}}$.

2) Effects of Moving the Electrodes Inward: Bipolar and tripolar measurements were performed to study the effect of moving the measurement electrodes inward. For the bipolar measurements three configurations were used (Fig. 1): measurement between the electrodes number 1 ($\mathrm{configuration = b1}$), measurement between the electrodes 2 ($\mathrm{configuration = b2}$), and measurement between the electrodes number 3 ($\mathrm{configuration = b3}$). The IR were calculated for EMG and stimulus pulse as $\mathrm{IR_{b1/2} = N_{b1}/N_{b2}}$ and $\mathrm{IR_{b1/3} = N_{b1}/N_{b3}}$.

Also for the tripolar measurements, three configurations were used: measurement between the center electrode and short circuited electrodes number 1 (Fig. 1) ($\mathrm{configuration = t1}$), measurement between the center electrodes and short circuited electrodes number 2 ($\mathrm{configuration = t2}$), and measurement between the center electrodes and short circuited electrodes number 3 ($\mathrm{configuration = t3}$). The IR was calculated for the S/Ns between the CAP and the EMG or stimulus peak-peak values as: $\mathrm{IR_{t2/1} = (S/N_{t2})/(S/N_{t1})}$ and $\mathrm{IR_{t3/1} = (S/N_{t3})/(S/N_{t1})}$.

3) Effects of Additional Short Circuiting: Tripolar measurements of CAPs, EMGs, and stimulus artefacts were performed to study the effect of additional short circuiting. Two configurations with and without additional short circuiting were used and compared with the results of the traditional tripolar configuration, $\mathrm{t_1}$, where the signal was measured from the center electrode versus electrodes 1, short circuited (Fig. 1). The two configurations with additional short circuiting are: measurement between the center electrode and electrodes number 2 (Fig. 1) with ($\mathrm{configuration = t2s}$) and without ($\mathrm{configuration = t2}$) short circuiting of electrodes number 1, and measurement between the center electrodes and the electrodes number electrodes 3 with ($\mathrm{configuration = t3s}$) and without ($\mathrm{configuration = t3}$) short circuiting electrodes number 1 and 2. The IR was calculated for the S/Ns between the CAP and the EMG or stimulus peak-peak values as: $\mathrm{IR_{t2s/t2} = (S/N_{t2s})/(S/N_{t2})}$ and $\mathrm{IR_{t3s/t3} = (S/N_{t3s})/(S/N_{t3})}$. Further, the improvement with respect to the standard tripolar configration, $\mathrm{t_1}$, was calculated: $\mathrm{IR_{t2s/t2} = (S/N_{t2s})/(S/N_{t1})}$ and $\mathrm{IR_{t3s/t3} = (S/N_{t3s})/(S/N_{t1})}$.

III. Results

The improvement rates and the statistics shown below are based on 30 implantations for the bipolar recordings and 29 implantations for the tripolar recordings. The reason for excluding a trial in the tripolar was that the recording failed to show a stimulus artefact.

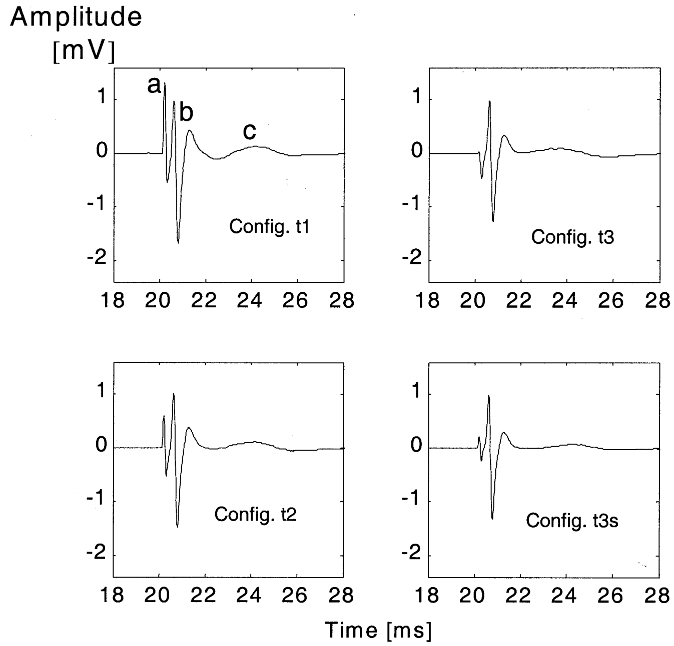

Fig. 3. Example of a recorded signal, with IR close to the average. (upper left) Recording with the standard tripolar configuration t1 (a: Stimulus artefact, b: CAP, and c: EMG wave). The results of moving the end electrodes (lower left) 1.5 mm inwards, (configuration t2), (upper right) 3 mm inwards (t3), and (lower right) 3 mm inwards and short circuit two additional end electrode pairs (t3s).

An example of the recorded CAP, EMG and stimulus pulse giving IR values close to the average is shown for different tripolar configurations in Fig. 3. The amplitude of the CAP is only slightly altered as compared with the interference when the length of the recording tripole is reduced by moving the tripole end electrodes 1.5–3 mm away from the cuff ends.

In Fig. 4, one of the results with the greatest improvements of the S/N ratio is shown. The total improvement with electrodes 1 and 2 short circuited gave IR values of 4.2 for the EMG and 4.8 for the stimulus pulse.

The results shown in Figs. 3 and 4 are obtained from the same cuff in two different rabbits, Fig. 4 being the first of the two implantations.

A. Effects of Short Circuiting on the Internal Cuff Field

The field inside the cuff was reduced by short circuiting, but the value of the reduction depended on the signal source and on the area of the electrodes used for short circuiting. For the EMG the average IRs, were $\mathrm{IR_{b2/s} = 2.00}$ and $\mathrm{IR_{b3/s} = 3.63}$, which shows that the field could be reduced to nearly one-quarter by short circuiting. Further, a double-sized short circuiting electrode area (the end electrodes 1 and 2 in Fig. 1 were shorted together in configuration b3s) gave a 180% increase in the field reduction, as compared with the use of a single pair of end electrodes for short circuiting. The first (Q1), second (Q2 = median), and third (Q3) quartiles [18] of the IR are shown in Fig. 5 for both the EMG and the Stimulus pulse.

For the stimulus pulse the field reduction was more than twice as high as for the EMG and the average IRs were $\mathrm{IR_{b2/s} = 5.00}$

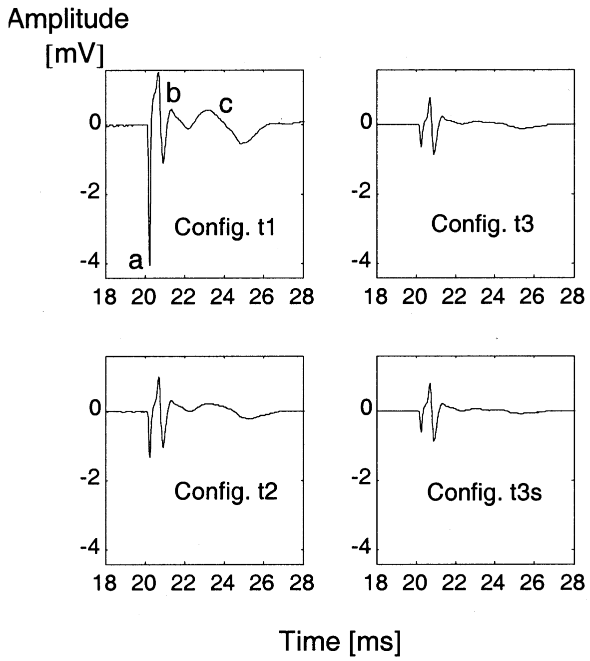

Fig. 4. Example of a recorded signal, with one of the highest IR. (upper left) Recording with the standard tripolar configuration t1, a: Stimulus artefact, b: CAP, and c: The EMG wave. The results of moving the end electrodes (lower left) 1.5 mm inwards, (configuration t2), (upper right) 3 mm inwards (t3), and (lower right) 3 mm inwards and short circuiting two additional end electrode pairs (t3s).

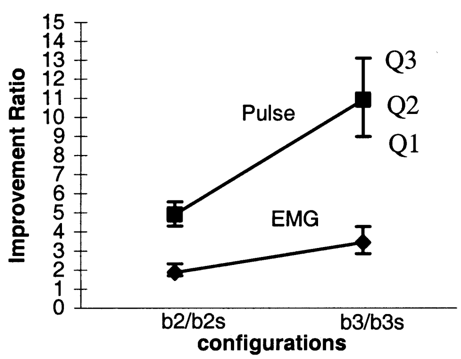

Fig. 5. IRs due to field reduction by short circuiting in bipolar recordings. The first, second, and third quartiles are shown for the IRs between the configurations b2 and b2s and between b3 and b3s.

and $\mathrm{IR_{b3/s}} = 11.43$ (Fig. 5). Thus, doubling the area of the short circuiting electrodes again increased the field reduction due to short circuiting with approximately a factor 2. But also short circuiting of a single electrode pair gave a considerable field reduction down to 1/5 of the original field. The reduction of the field due to short circuiting was statistically significant with P values less than 2×10^{-6} for all the abovementioned IR values.

B. Effects of Moving the Electrodes Inward

Moving the end electrodes used for bipolar recording inwards in 1.5 mm steps (the width of an electrode plus the space between the electrodes), by choosing different end electrode pairs (Fig. 1), gave only a small but consistent reduction of the interfering signals in the bipolar configurations as compared with

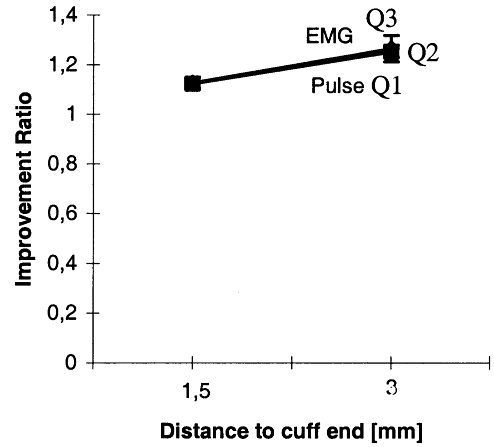

Fig. 6. Effects of moving the electrodes inwards in bipolar measurements. The IRs are shown for the two configurations b2 and b3, relative to b1. The first, second, and third quartiles are shown.

the standard bipolar configuration, b1 (Fig. 1). For configuration b2, where the electrodes are moved approximately 1.5 mm further inwards, the average IR was: $\mathrm{IR_{b1/2}} = 1.13$ for the EMG and $\mathrm{IR_{b1/2}} = 1.12$ for the stimulus pulse. The first, second, and third quartiles of the IR are shown in Fig. 6 for both the EMG and the Stimulus. For configuration b3, where the electrodes are moved approximately 3 mm inwards, the average IR was: $\mathrm{IR_{b1/3}} = 1.27$ for the EMG and $\mathrm{IR_{b1/3}} = 1.25$ for the stimulus pulse (Fig. 6). All the abovementioned improvements were statistically significant with P values less than 2×10^{-6}.

For the tripolar measurements the field reduction due to an increased distance from the end electrodes to the cuff end was larger. For a distance of 1.5 mm the average IRs were $\mathrm{IR_{t2/1}} = 1.33$ for the EMG and $\mathrm{IR_{t2/1}} = 1.62$ for the stimulus pulse as compared with the standard tripolar configuration (using electrodes no. 1 as the end-electrodes). This was statistically significant with P values less than 0.001. For an increased electrode cuff end distance of 3 mm the IRs became 13%–33% larger: $\mathrm{IR_{t3/1}} = 1.50$ for the EMG and $\mathrm{IR_{t3/1}} = 2.15$ for the stimulus pulse (P values were 0.0007 and 0.0003), and the field was reduced to only half of the interference recorded by the traditional tripolar cuff configuration. The first, second, and third quartiles of the IR are shown in Fig. 7 for both the EMG and the Stimulus pulse.

Moving the electrodes away from the cuff end alters the nerve signal, since it is equivalent to reducing the length of the cuff which reduces the nerve signal [3], [5], [11]. The reduction of the nerve signal is on average (Table I) 22% as the tripole length changes from 27 to 20 mm.

At the same time, the average reduction of the EMG and the stimulus pulse was larger (Table I) which gave an improvement of the S/N ratio.

The first, second, and third quartiles of the normalized amplitudes are shown in Fig. 8. The size of the reduction in the interference pick up is decreasing as the electrodes are moved further away from the cuff end, and between a distance of 1.5 and 3 mm the loss of nerve signal becomes close to the decrease of interference which means that the distance of 3 mm is close to optimal.

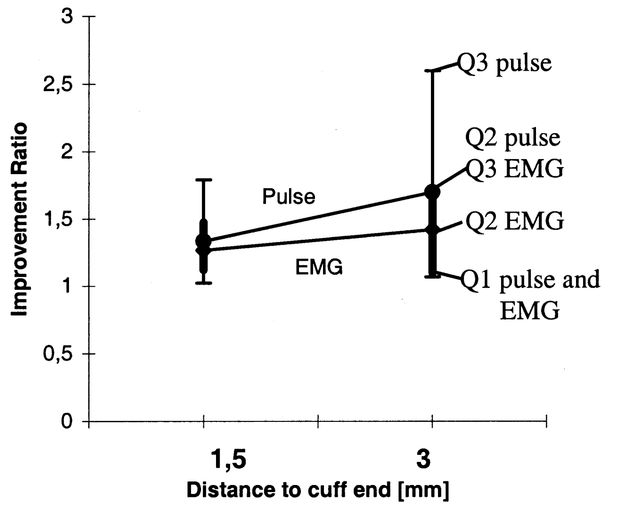

Fig. 7. Improvement of the S/N ratios in tripolar recordings due to moving the end electrodes away from the cuff end. The first, second, and third quartiles are shown for the IRs. The quartiles shown with the bold line refers to the EMG.

TABLE I
AVERAGE REDUCTION OF THE SIGNALS RECORDED WITH A TRIPOLAR CUFF CONFIGURATION, DUE TO MOVING THE ELECTRODES INWARD

Distance to cuff end [mm]	0.2	1.5	3.0
CAP	1	0.89	0.78
EMG	1	0.72	0.66
Stimulus	1	0.73	0.57

C. Effects of Additional Short Circuiting

Additional short circuiting had only a limited effect on the S/N ratio in the tripolar recordings. With only a single set of additional short circuiting electrodes (configuration t2s) the average IRs were: $\mathrm{IR}_{t2s/t2} = 1.06$ for the EMG and $\mathrm{IR}_{t2s/t2} = 1.11$ for the stimulus pulse. The result for the EMG had a P value of 0.06 and was statistically significant while the result for the stimulus artefact was nonsignificant with a P value of 0.6. The first, second, and third quartiles of the IRs are shown in Fig. 9 for both the EMG and the Stimulus pulse. Using both the electrodes 1 and 2 for additional short circuiting doubled the increase of the S/N ratios, which gave an improvement of 18%–24%. The average improvements rates were: $\mathrm{IR}_{t3s/t3} = 1.20$ for the EMG and $\mathrm{IR}_{t3s/t3} = 1.18$ for the stimulus artefact. This was statistically significant for the EMG ($\mathrm{P} = 0.016$) but still nonsignificant for the stimulus ($\mathrm{P} = 0.28$).

Comparing the results for the configurations with additional short circuiting with the standard tripolar configuration (t1) gives the total achievable improvement of the S/N ratios due to the increased distance between the cuff end and the tripole end electrodes and due to the additional short-circuiting. This gave the following average IRs: $\mathrm{IR}_{t2s/t1} = 1.40$ for the EMG and $\mathrm{IR}_{t2s/t1} = 1.60$ for the stimulus pulse, and $\mathrm{IR}_{t3s/t1} = 1.73$ for the EMG and $\mathrm{IR}_{t3s/t1} = 2.27$ for the stimulus pulse (Fig. 10). The P values for these four IR values were all less than 0.0001.

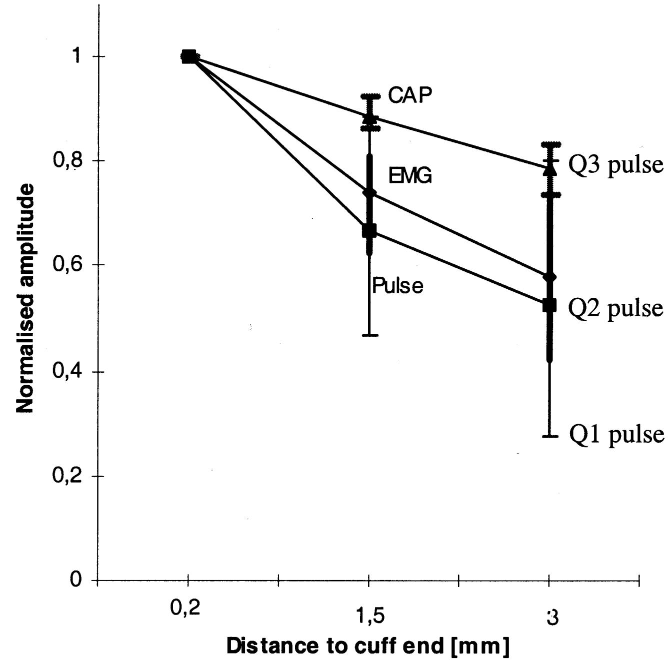

Fig. 8. Signal dependency on distance from tripole end electrodes to cuff end. The amplitudes are normalized with the amplitudes from the recording with the end electrodes at the cuff end, t1. The first, second, and third quartiles of the normalized amplitudes are shown. The quartiles shown with bold refer to the EMG, the quartiles shown with grey refer to the nerve signal and the solid line refers to stimulus pulse.

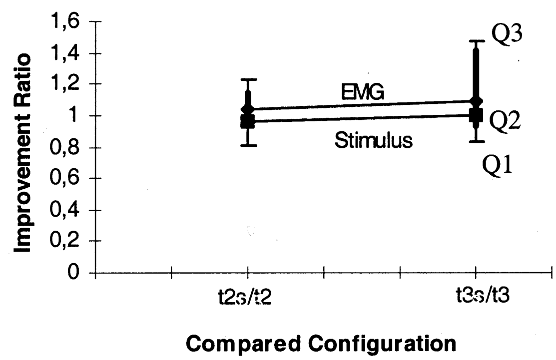

Fig. 9. The effect of additional short circuiting in tripolar recordings. The first, second, and third quartiles are shown for the IRs between the configurations t2 and t2s and between t3 and t3s. The bold line refers to quartiles of the EMG and the solid line refers to the stimulus pulse.

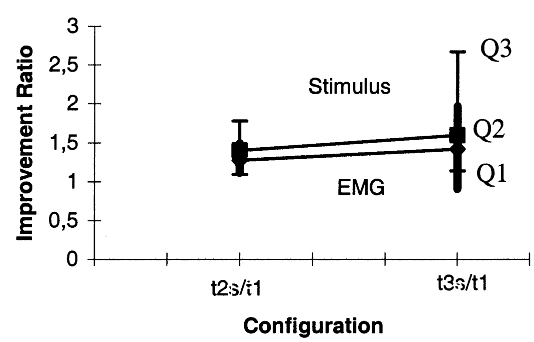

Fig. 10. The total effect of additional short circuiting and moving the electrodes inwards in tripolar recordings. The first, second, and third quartiles are shown for the IRs between the configurations t2s and t1 and between t3s and t1. The bold line refers to quartiles of the EMG and the solid line refers to the stimulus pulse.

IV. Discussion

A. Field Reduction,

In an ideal tripolar cuff configuration, the interference caused by sources outside the cuff is perfectly cancelled. But imperfect electrode placement, asymmetry in the electrode-tissue impedances, asymmetry in the tissue impedance distribution inside the cuff, and an imperfect cuff closure are unavoidable in real cuffs. All these imperfections attribute to a less than perfect noise cancellation. For each of these cases, a reduction of the interfering field inside the cuff will reduce the effect of the imperfection. This reduction of the field inside the cuff due to external sources was obtained by short circuiting. The effectiveness of the short circuiting path depends on the signal source and on the area of the electrodes used for short circuiting. With a 100% increase of the area of the shorted electrodes, the short circuiting path became approximately twice as effective. The EMG interference was on average reduced with a factor 5 while the interference from the stimulus pulse was on average reduced with a factor 11 as compared with the fields without short circuiting. These reductions are larger than the maximum reduction of a factor two described in a model study [8]. Reasons for this discrepancy can be the sensitivity of the reduction to source (e.g., frequency content) and cuff specific parameters, because of the use of a different source of the field, a different cuff and a different end-electrode size. Furthermore, the distance between the source and the cuff is also important, especially when they are close together (within 1.5 cm) [12]. It could be argued that the high reduction of the field, when a larger end-electrode area is used, is partly due to the fact that the end electrodes of the bipole in the measurements are moved inward [9] when two electrodes (electrodes 1 and 2 in Fig. 1) are used for short circuiting. But, as shown in the results, moving the electrodes inwards had only little effect on the bipolar measurements. The strong effect of increasing the area of the short circuiting electrodes emphasises the strong effect of short circuiting and the importance of keeping the impedance of the electrode electrolyte interface low.

B. Effect of Moving the end Electrodes Inwards

Moving the end electrodes away from the cuff end had only little effect on the pick up of interfering signals in the bipolar recordings, as compared with the effect of short circuiting. The largest reduction of the pick up of 25% was obtained with the largest distance from the electrodes to the cuff ends which was approximately 3 mm. This configuration reduced the distance between the recording electrode pair by about 6 mm or 22%, which should cause a reduction of the voltage between the end electrodes of about 22% if the field was perfectly linear. The reduction of the stimulus pulse was slightly larger than the one of the EMG.

In the tripolar recording, the effect was larger but also biggest for the longest distance between the end electrode and the cuff end. The maximum improvement of the S/N ratio was 50%–100% and was highest for the stimulus pulse.

The reason why moving the end-electrodes inwards reduces the interference pick up is probably mainly due to reduction of end effects related to the linearization of the field inside the cuff induced by external sources, which is also suggested in [9]. But also partly because the distance between the electrodes directly affects the voltage because of the linear potential field inside the cuff. The fact that the effect of moving the electrodes inward is larger for the tripolar recording than for the bipolar could indicate that short circuiting itself might affect the field linearization at the cuff ends and increase the abovementioned end effects.

The improvement of the S/N ratio by moving the end electrodes inwards depends of the change in both interfering signal and the nerve signal. The amplitude of a single fiber action potential depends strongly on the distance between the end electrodes of the recording tripole [3], [5], [11], and this dependency is even more prominent for the compound nerve signal [3]. Therefore, the choice of distance to the end of the cuff is a tradeoff and the ideal distance depends on cuff length and fiber diameter. The change of tripole length from 27 mm to 20 mm due to moving the end electrodes away from the cuff end gave an average reduction of the nerve signal amplitude of 22%. Assuming the fiber diameters being in the range of 5–10 μm, this is more than expected from amplitude studies of single fiber action potentials [5], [11], but agrees well with studies of the dependency of the root mean square value of the electroneurogram on cuff length [3]. As long as the interference is reduced more than the nerve signal the electrodes can be moved further away from the cuff end. In the present study, a distance of 3 mm was close to optimal. For shorter cuffs the nerve signal may decline more rapidly and less than 3 mm may be optimal.

C. Effects of Additional Short Circuiting

The effect of additional short circuiting was not as strong as of moving the end electrodes away from the cuff ends, but the increase of the S/N ratio clearly depends on the size of the short circuiting electrodes. The maximum achieved improvement was 18%–24%, and these improvements were significant only for the EMG.

Even though the improvement of additional short circuiting is small, it is significant for the EMG and we suggest an alternative tripolar cuff configuration with wide additional end electrodes for additional short circuiting. Hereby the end electrodes of the recording tripole are moved away from the cuff end. With such a configuration (total additional end electrode width = 2 mm and distance between tripole end electrodes and cuff end = 3 mm) a total S/N improvement of 73% for the EMG and 127% for the stimulus pulse was obtained with a 27 mm long cuff.

A reduction in the S/N ratio as a result of using a shorter cuff will mainly be due to loss of nerve signal. For a 10-μm-diameter fiber, a change of cuff length from 27 to 20 (where 7 mm are used for the additional end electrodes, resulting in a 13-mm-long recording tripole) the signal loss is expected to be 56% [3]. Since the new configuration on its own improves the S/N ratio with 73%, shortening the cuff to 20 mm gives no loss in S/N ratio as compared to using the traditional tripolar configuration in a 27-mm-long cuff. Therefore, in addition to using this new configuration for improving the S/N ratio for a fixed cuff length, it can also be used to reduce the cuff length without impairing the S/N ratio.

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