Med. & Biol. Eng. & Comput., 1978, 16, 513–518

# Analysis of gastric electrical signals from surface electrodes using phaselock techniques
# Part 2–System performance with gastric signals

R. H. Smallwood

Sheffield University and Area Health Authority (Teaching), Department of Medical Physics, Hallamshire Hospital, Sheffield, England

**Abstract**—*The 0·05 Hz (3 cycle/min) electrical activity from the human stomach was first recorded in 1922 by Alvarez, using electrodes placed on the skin. The major problem with surface electrode recordings is the poor signal/noise ratio. The application of a phaselock system, using a smaller number of readily available integrated circuits, to this problem has been described and in the paper the performance of this system is discussed.*

**Keywords**—*Gastric electric potentials, Phaselock techniques*

## 1 Introduction

THE FIRST part of this paper (SMALLWOOD, 1978) described the design of a phaselock system for the analysis of gastric electrical activity, together with the performance of the system at known signal/noise ratios. The performance of the system with gastric electrical signals recorded from surface electrodes is described below together with the results obtained using fast Fourier transforms (f.f.t.s).

The recording and fast Fourier transform analysis of the gastric electrical signals has been described previously (BROWN *et al.*, 1975; SMALLWOOD, *et al.*, 1975). The recordings were made on normal subjects who were fasted overnight. Three pairs of bipolar electrodes were placed over the gastroduodenal area and the electrical activity was recorded on an FM tape recorder. Recordings were made for one and a half hours before a meal, and one and a half hours after.

## 2 Analysis of signals

As described in Pt. 1, the phaselock system was designed for operation at 64 times real time with a centre frequency of 3·2 Hz and a frequency range of 2·2–4·2 Hz (equivalent to 2·06–3·94 cycles/min in real time). The tape recorded signals were replayed at 64 times the recording speed of 15/16 in/s. The signals were filtered before the phaselock loop (3 dB bandwidth 2·2–4·2 Hz, roll-off 6 dB/octave). The original signal, the filtered signal, the instantaneous frequency of the phaselock-loop oscillator and the e.m.p. average frequency and the e.m.p. standard deviation (calculated from the instantaneous frequency) were recorded on a chart recorder for subsequent analysis. Indication that the loop was locked was provided by the e.m.p. standard deviation, which was gated by the lock signal, so that the e.m.p. standard deviation was only displayed when the loop was locked to the input signal (Fig. 1). A total of 28 recordings, covering (in real time) about 21 h before and 21 h after the meal, were analysed. A marker was recorded on the chart every second (64 s in real time) and was used as the time indicator in the subsequent analysis. A time constant of 1 s was used for the calculation of the e.m.p. mean and e.m.p. standard deviation and the switched loop filter was used throughout.

The chart records were analysed manually. No measurements were made until the loop had been locked to the signal for at least 1 s, that is, measurement started at the second time marker after the indication of lock. The e.m.p. mean and the e.m.p. standard deviation were then measured every second until lock was lost.

## 3 Results

The percentage of the total recording time for which the system was locked is shown in Fig. 2 for all the channels before and after the meal and in Fig. 3 for the best channel in each record. The best channel was defined as the channel with the greatest percentage of lock time exceeding three seconds (see below). The cumulative time for which the system locked for more than 1, 2, 3, 4, 5, 10 and 20 s was measured and is expressed as a percentage of the record length. Before these figures can be compared with those for the fast Fourier transform

*Received 2nd November 1977*

0140–0118/78/0757–0513 $1·50/0

analysis of the same data, it is necessary to establish how long the loop must be locked before the e.m.p. mean frequency is a reliable measure of the signal frequency. If the e.m.p. mean frequency is measured with a time constant $\tau$, then the contribution of instantaneous frequencies occurring more than $3\tau$ before the present is less than 5%. The period for which the loop must be locked before meaningful frequency measurements can be made has, therefore, been set at $3\tau$ (three seconds in the present analysis). Table 1 compares the percentage of the total time for which the loop is locked for times exceeding three seconds, for the best channel in each record and for all three channels in each record, with the percentage of the total number of fast Fourier transforms for which a significant peak was found, again for the best channel in each record and for all three channels. The definition of a frequency transform with a significant peak is discussed in SMALLWOOD *et al.*, 1975. In 25 out of 28 records the best channel was the same for frequency transforms and for the phase-lock system.

The e.m.p. mean frequency and e.m.p. standard deviation for a 21 s stretch of data are shown in Fig. 4. The values found for the three channels of

*Table 1*

| | Best channel, % | | All channels, % | |
|---|---|---|---|---|
| | f.f.t. | p.l.l. | f.f.t. | p.l.l. |
| Before meal | 59 | 41 | 29 | 22 |
| After meal | 74 | 47 | 50 | 34 |

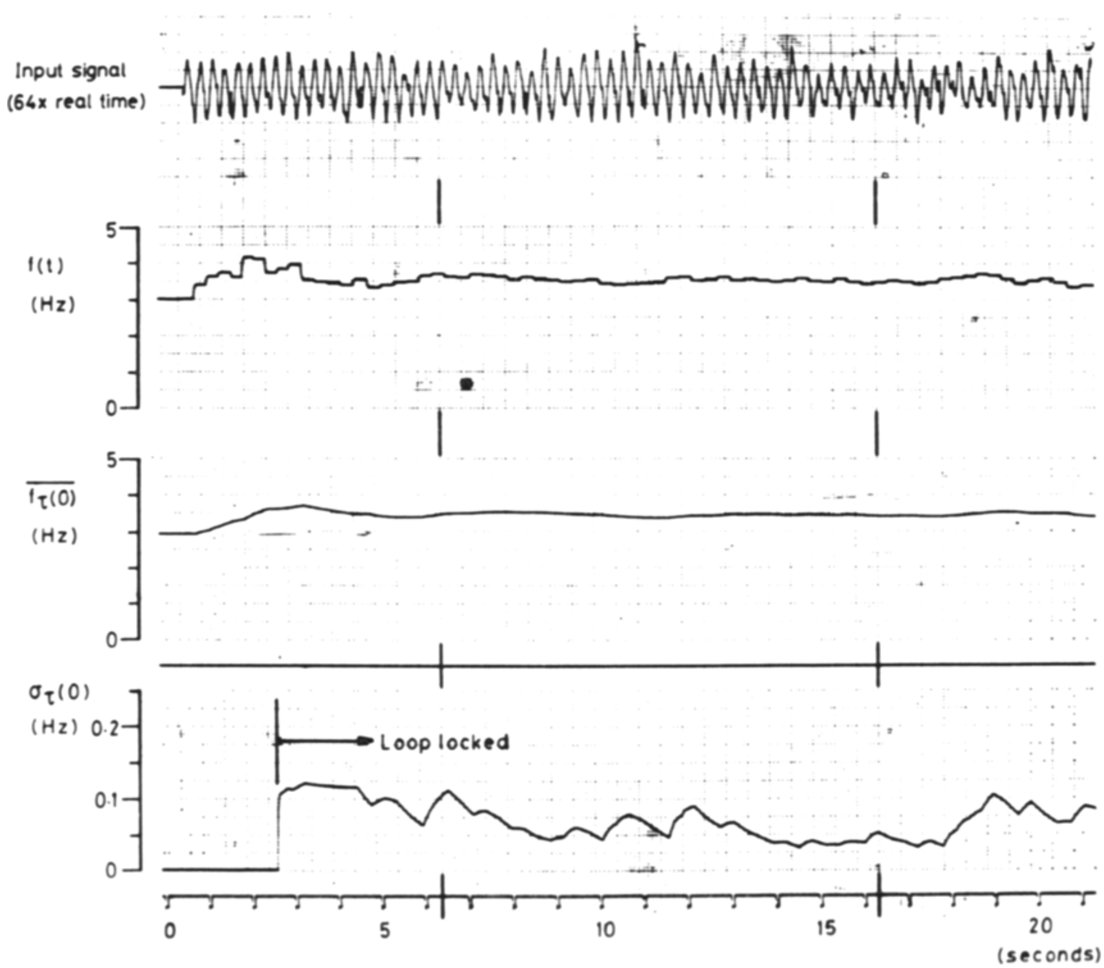


*Fig. 1 Input and outputs of phaselock loop. From top to bottom:*
*(1) Input to system (gastric electrical signal recorded from surface electrodes)*
*(2) Instantaneous frequency f(t) of p.l.l. oscillator*
*(3) E.M.P. mean frequency $\overline{f_\tau(0)}$*
*(4) E.M.P. standard deviation $\sigma_\tau(0)$ both calculated with $\tau$ = 1 s*

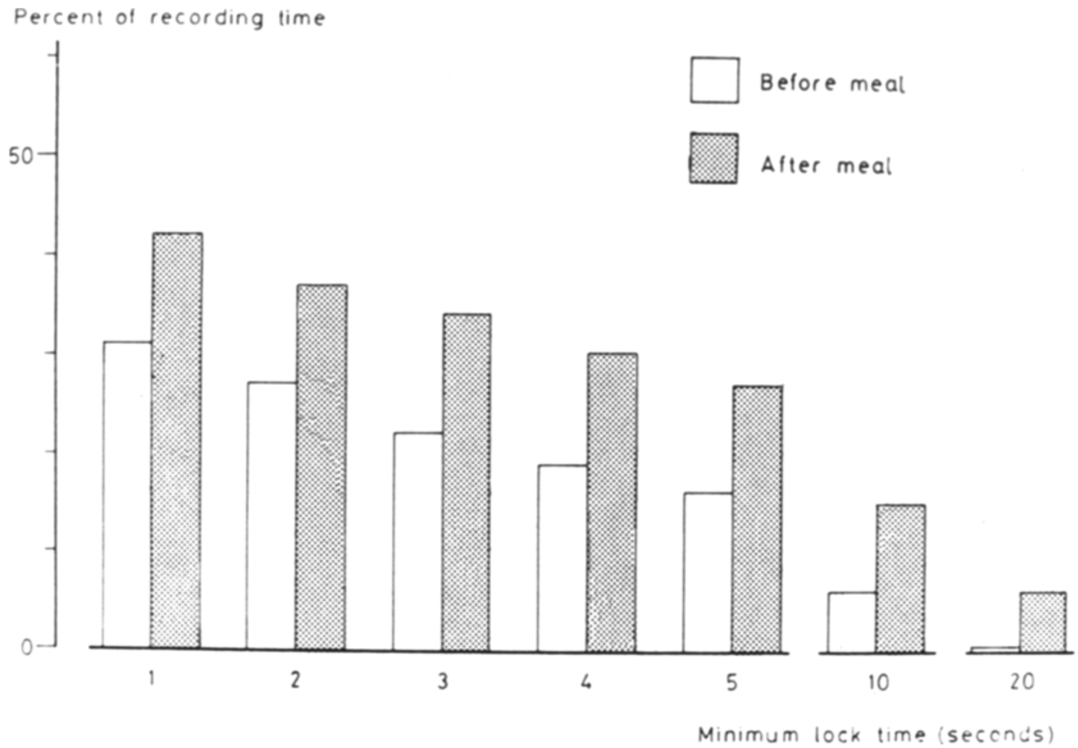


*Fig. 2 Cumulative time for which the phaselock system is locked to the input signal, expressed as a percentage of the total recording time, for minimum lock periods of 1–20 s. Cumulative time for all three channels of data, before and after a meal*

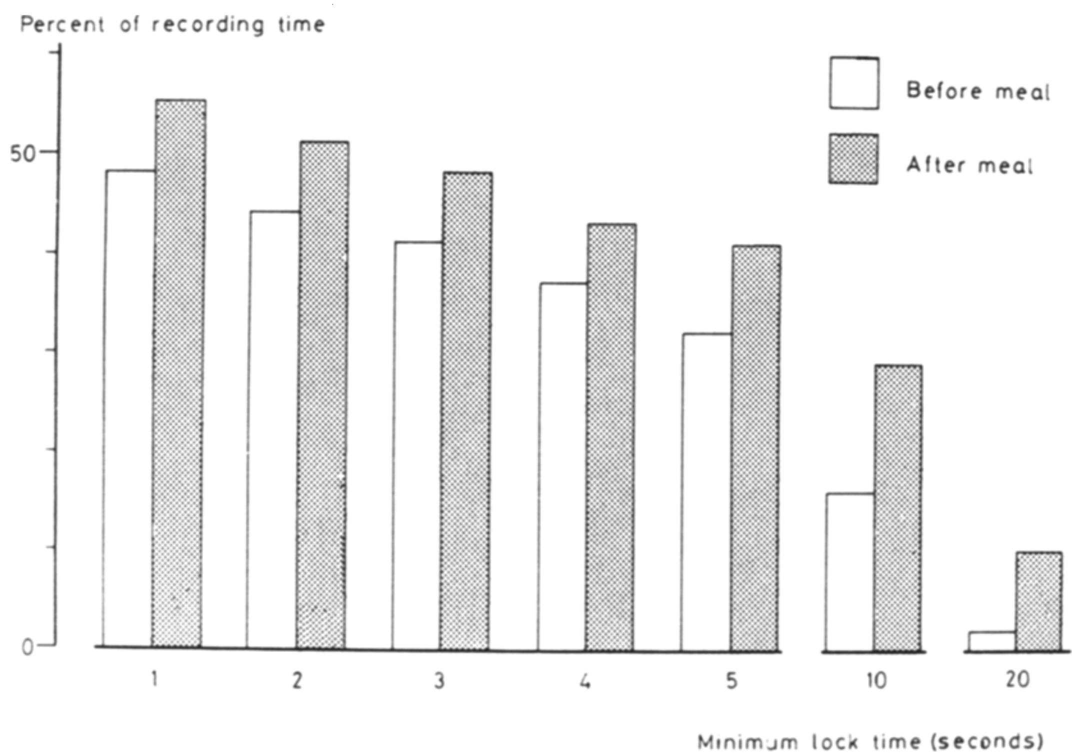


*Fig. 3 As Fig. 2, for the best channel of data in each record*

gastric electrical activity are plotted at 1 s intervals and the frequency found by fast Fourier transform is also shown. At 64 times real time, the time window for the f.f.t. is 10·7 s and the frequency resolution is ± 0·045 Hz; i.e. channel width (1/10·7) Hz. In the two time windows shown, the frequency found in all three channels of data was the same. The e.m.p. values of frequency correspond closely with the frequencies calculated by the f.f.t. All three channels show corresponding changes in e.m.p. frequency with time which are averaged by the Fourier transform. The significance of the changes in frequency is discussed below.

## 4 Significance of changes in e.m.p. frequency

OTTERMAN (1960) describes the calculation of the exponentially mapped past mean and variance, but does not indicate how these statistical variables can be used to determine whether two means are significantly different. The problem does not appear to have been covered in the subsequent literature. An estimate of the number of degrees of freedom is needed. For a conventional moving average, the number of degrees of freedom would be the number of points over which the average was taken. The e.m.p. mean is a weighted moving average over an infinite number of points, the weighting function being an exponential with time constant $\tau$. If the contribution to the number of degrees of freedom of each point averaged is similarly weighted; i.e. the present point is given a weight of one, the preceding point of weight of $\exp(-t/\tau)$ and so on, where $t$ is the time interval between points, then the number of degrees of freedom $N$ is given by

$$N = \text{integer part of } \sum_{n=0}^{\infty} \exp(-nt/\tau)$$

$$= \text{integer part of } \sum_{n=0}^{\infty} \exp(-n/f\tau)$$

$$\text{where } f = \frac{1}{t} = \text{instantaneous frequency.}$$

For a time constant $\tau = 1$s, the number of degrees of freedom are

$f \leqslant 3{\cdot}4$ Hz $\quad N = 3$

$f > 3{\cdot}4$ Hz $\quad N = 4$

Measurements of the e.m.p. frequency which are separated by $3\tau$ s or more are taken as independent, as the first measurement will contribute less than 5% to the second measurement. If Student's $t$ test is now used to calculate the significance of the

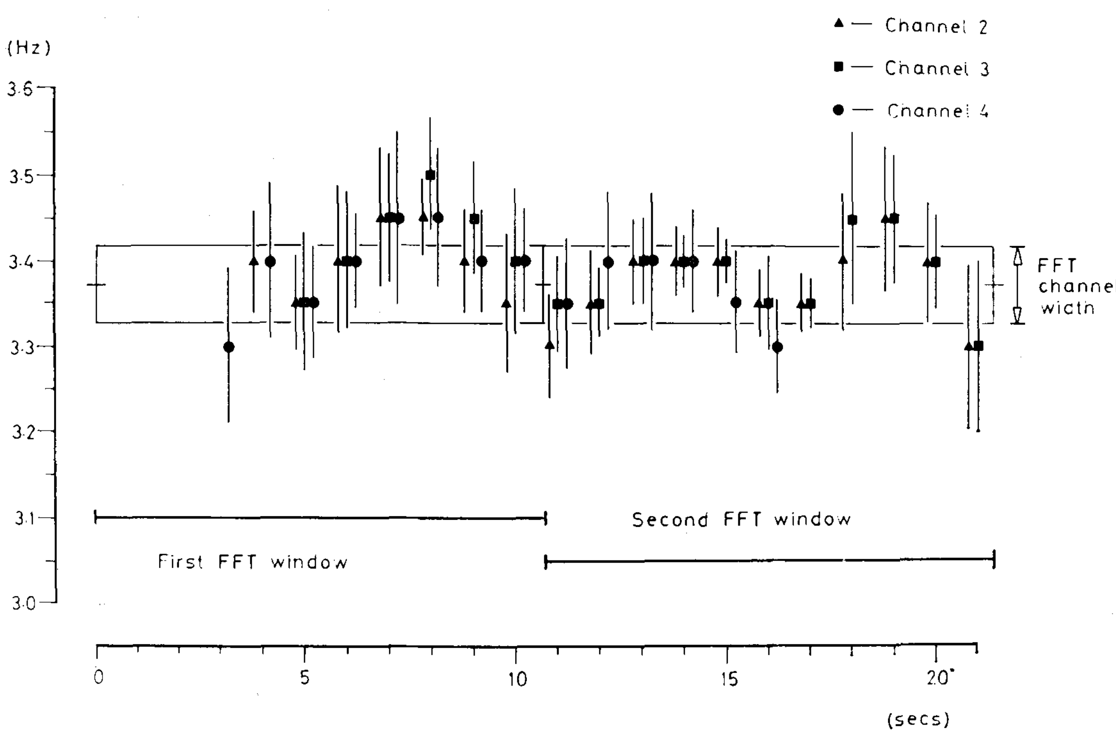


*Fig. 4 Analysis of a 21 s stretch of 3 channels of data recorded from surface electrodes, showing results obtained with f.f.t. analysis and p.l.l. analysis. E.M.P. mean ± e.m.p. standard deviation ($\overline{f_\tau(0)} \pm \hat{\sigma}_\tau(0)$) for all three channels, together with two periods of f.f.t. analysis*

changes in frequency shown in Fig. 4, the following results are obtained for channel two at five, eight, eleven and fourteen seconds after the start of the recording:

Time interval

5– 8 s $p < 0{\cdot}05$

8–11 s $p < 0{\cdot}01$

11–14 s $p < 0{\cdot}05$

These three significant changes in gastric frequency occur within 9 s; i.e. within the period of a single Fourier Transform.

## 5 Discussion

Fast Fourier transform analysis is well established as a method of signal processing and gives a standard against which other methods of analysis can be compared. The length of the time window for the f.f.t. is set by the frequency resolution required and has been taken as about thirty cycles for the gastroduodenal data, to give a frequency resolution of about 3% (LINKENS and CANNELL, 1974; BROWN *et al.*, 1975). For the gastric electrical activity at about three cycles/minutes (real time), this gives a time window of about 10 min. It is not possible to measure changes in frequency which take place within the 10 min period. As discussed elsewhere (BROWN *et al.*, 1975) and shown in Table 1, the success rate for fast Fourier transformation is different before and after a meal and varies between 59 and 74% of the recording time for the best of three channels of data recorded from surface electrodes. The presence of a significant peak in a particular transform does not, of course, imply that the activity was present throughout the 10 min period. The Fourier transform is well suited to the analysis of signals containing more than one frequency and an examination of the harmonics present will give an indication of waveshape.

In contrast, the phaselock loop will only lock onto a single signal frequency and the range of operation is limited to less than one octave in order to ensure that the loop does not lock onto harmonics of the signal of interest. However, the phaselock loop will track a signal with a period which is changing from cycle to cycle, the accuracy of the tracking being dependent on the signal/noise ratio and the rate of change of frequency. The output of the phaselock loop can be used to give a continuously updated value of the mean frequency of the signal and the standard deviation of the frequency can be calculated using the e.m.p. method of OTTERMAN (1960). Given certain assumptions about the number of degrees of freedom, it can be shown that significant changes in gastric frequency can take place within the period of a single f.f.t. The percentage of the recording time for which the loop was locked for more than 3 s was 41% before the meal, and 47% after the meal, for the best channel in each record. These figures are lower than for the f.f.t., but are not directly comparable, as they indicate the presence of a frequency measurement in a 1 s interval, whereas the f.f.t. shows that a significant frequency was present at some time during a 10·7 s interval. It should also be noted that the first 2 s of each lock period are discarded for the purpose of frequency measurement.

In the initial design of the loop, it was assumed that the maximum rate of change of frequency that the loop had to track was twenty per cent in ten cycles. The present analysis would indicate that the maximum rate of change of frequency is no more than a third of this figure. The bandwidth of the narrowband filter could therefore be reduced by a factor of 3, which should improve the performance of the loop with noisy signals and increase the percentage lock time.

Manual analysis of the output of the phaselock system is exceedingly laborious. It would be a simple task to output the e.m.p. mean frequency and e.m.p. standard deviation on a digital printer with the printing controlled by the lock indicator.

The discussion in this paper has been confined to the use of the phaselock system with signals recorded from surface electrodes. The system has also been used to analyse a simultaneous recording from a gastric mucosal electrode and two pairs of surface electrodes. The phaselock loop remained locked to the mucosal signal throughout the recording.

## 6 Conclusion

The design and performance of a simple phaselock system for tracking low-frequency biological signals has been discussed. The system was used at 64 times real time but could operate online after appropriate scaling of time constants. The exponentially mapped past mean frequency and standard deviation have been calculated and the frequencies obtained from surface electrode recordings of gastric electrical activity have been compared with fast Fourier transform analysis of the same 28 records. The relative advantages and disadvantages of the two methods have been discussed. In particular, it has been shown that statistically significant variations in gastric electrical frequency can take place within the period of a single frequency transform. Preliminary results indicate that the method may be particularly useful in the analysis of mucosal and serosal recordings of gastroduodenal electrical activity.

*Acknowledgments*—This work was suggested by T. S. Nelsen, and I am grateful to him and to D. A. Linkens, B. H. Brown and H. L. Duthie for suggestions and criticism.

## References

BROWN, B. H., SMALLWOOD, R. H. DUTHIE, H. L. and STODDARD, C. J. (1975) Intestinal smooth muscle electrical potentials recorded from surface electrodes. *Med. & Biol. Eng.* **13,** 97–103.

LINKENS, D. A. and CANNELL A. E. (1974) Interactive graphics analysis of gastrointestinal electrical signals. *IEEE Trans.* **BME-2,** 335–339.

OTTERMAN, J. (1960) The properties and methods for computation of exponentially mapped past statistical variables. *IRE Trans.* **AC-5,** 11–17.

SMALLWOOD, R. H., BROWN, B. H. and DUTHIE H. L. (1975) An approach to the objective analysis of intestinal smooth muscle potentials recorded from surface electrodes. Proceedings of the 5th International Symposium on Gastrointestinal Motility, Leuven, Belgium.

SMALLWOOD, R. H. (1978) Analysis of gastric electrical signals from surface electrodes using phaselock techniques: Pt. 1—System design. *Med. & Biol. Eng. & Comput.*, **16,** 507–512.


## Analyse des signaux électriques gastriques provenant d'électrodes de surface à l'aide de techniques à phase rigide
## Deuxième partie—Performance du système pour les signaux gastriques


**Sommaire**—L'activité électrique de 0·05 Hz (3 cycles/mn) de l'estomac humain a été enregistrée pour la première fois en 1922 par Alvarez à l'aide d'électrodes placées sur la peau. Le problème majeur dans l'enregistrement avec des électrodes de surface est le mauvais rapport signal/bruit. L'application d'un système à phase rigide utilisant un plus petit nombre de circuits intégrés faciles à se procurer à ce problème est décrite et l'article discute les performances de ces systèmes.


## Analyse gastrischer elektrischer Signale von Hautelektroden unter Anwendung phasenstarrer Techniken
## Teil 2—Wirkungsweise des Systems bei gastrischen Signalen


**Zusammenfassung**—Die elektrische Aktivität des menschlichen Magens von 0·05 Hz (3 Perioden pro Minute) wurde erstmals im Jahre 1922 durch Alvarez mittels Hautelektroden aufgezeichnet. Der schlechte Rauschabstand ist bei den Aufzeichnungen mittels Hautelektroden das wesentliche Problem. Die Behandlung dieses Problems durch Anwendung eines phasenstarren Systems mit wenigen handelsüblichen integrierten Schaltungen ist beschrieben worden und in dieser Dokumentation wird die Wirkungsweise des Systems erörtert.