

## Short-distance radio telemetry of biopotentials in occupational medicine

*Aloš Mikiška*

### *Zusammenfassung*

Es werden zwei Typen von radiotelemetrischen Sendern beschrieben für die Übertragung bioelektrischer Spannungen beim Menschen in Bewegung, besonders während der Arbeit. Das erste Modell eignet sich für Spannungen der Größenordnung von 1 Millivolt mit Frequenzkomponenten im Bereich von 0,5 bis 160–300 Hz, zum Beispiel EKG oder Summations-EMG. Das zweite Modell wurde speziell für die Herzschlagfrequenzmessung konstruiert; das übertragene Frequenzband ist für diesen Zweck auf 4 bis 30 Hz beschränkt. Der Hochfrequenzoszillator (40–95 MHz) ist entweder amplituden- oder frequenzmoduliert; keine Sendeantenne wird verwendet, so daß die Hochfrequenzenergie nur von der Oszillatortspule, den Elektrodenableitkabeln sowie vom Körper der Versuchsperson ausgestrahlt wird. Diese Konstruktion ermöglicht es, den Sender unter der Bekleidung der Versuchsperson zu plazieren, was einen Schutz gegen Temperaturschwankungen und andere schädliche Einwirkungen des Arbeitsmilieus (Staub, Ätzmittel usw.) bietet. Der Sender unter der Kleidung kann keinen elektrischen Unfall (durch Berührung von Netzspannungsleitungen usw.) verursachen und bleibt für andere Personen unsichtbar, wodurch ein ungünstiger emotionaler Streß der Versuchsperson vermieden wird.

In beiden Modellen wird eine Hilfstägerfrequenz von ungefähr 1200 Hz, frequenzmoduliert mit einem ziemlich hohen Frequenzhub ( $\pm 30\%$ ) seines Mittelwertes,

### *Summary*

Two types of radiotelemetry transmitters were designed for recording biopotentials in moving human subjects, especially during occupational work. The first type is suitable for potentials of order 1 millivolt and with frequency components in the range 0.5 to 160–300 c/s, e.g. electrocardiogram or summation electromyogram. The second type is designed specifically for heart rate counting, owing to the signal frequency band being limited from 4 to 30 c/s. The very high frequency oscillator (40 to 95 Mc/s) is frequency- or amplitude-modulated; no transmitting antenna is used, so that the radio-frequency energy is radiated only by the oscillator coil, electrode leads and the subject's body. This construction allows the transmitter to be worn under the subject's clothes, preventing thus damage to the transmitter from too high or low environmental temperature or other unfavourable factors (dust, corrosive substances, etc.). Moreover, carrying the transmitter under the clothes excludes the hazard of electrical injury due to accidental contact with mains supplies and makes the transmitter practically invisible to co-workers and other persons, reducing thus emotional stress from medical examination during work.

A subcarrier frequency, approximately 1200 c/s, frequency-modulated with an unusually high deviation ( $\pm 30\%$ ) of the mean value, is used in both transmitter types. This subcarrier frequency can be recorded on the magnetic tape and used for subse-

verwendet. Diese Hilfsträgerfrequenz kann auf einem Tonbandgerät aufgenommen und später beim Abspielen für graphische Registrierung oder automatische Analyse benutzt werden. Wenn die Hilfsträgerfrequenz durch das EKG-Potential frequenzmoduliert wird, schwankt die entsprechende Tonhöhe im Rhythmus der Herztätigkeit, was die Herzschlagzählung ohne weitere Auswertungsgeräte ermöglicht.

Die Reichweite der drahtlosen Übertragung mit den beschriebenen Sendern beträgt von 30 (im Gebäude) bis zu 100 m (im Freien). Der Stromverbrauch (7–9 Milliampere von einer 9 V Batterie) gewährt eine Betriebsdauer von ungefähr 20 bis 30 Stunden ohne Batteriewechsel. Das Gewicht (160 bzw. 250 Gramm) könnte durch Mikrominiaturisation noch reduziert werden; jedoch für eine Routineverwendung in der Arbeitsphysiologie und verwandten Disziplinen erscheint die Konstruktion aus Standard-Bestandteilen ökonomischer zu sein.

quent graphic recording and/or automatic analysis of the bioelectric signal. – If the subcarrier modulation is performed with the electrocardiographic potential, the pitch of the corresponding tone varies in the rhythm of heart action, making thus possible immediate distant heart rate counting.

The range of telemetry is several tens of meters. The current drain, 7 to 9 milliamperes from a 9 volt battery, allows satisfactory operation for approximately 20 to 30 hours. The weight, 160 or 250 grams, could be further reduced by using integrated circuitry; nevertheless, the use of standard components seems to be more economical for routine examination in occupational physiology and related branches of medicine.

In connection with increasing mechanization and automation in almost all branches of human work, new tasks emerge in occupational medicine. Classical methods of work physiology must therefore be supplemented or partially replaced by new examination techniques; some of the latter making possible the investigation of various physiological functions of the examined human subject during his natural occupational work.

This task is of interest not only for obtaining mean statistical values for healthy people (which constitutes a problem of occupational physiology), but also for studying subjects suffering from various diseases (especially chronic) during natural living and working conditions. In reviewing the development of knowledge on physiological functions during occupational work or during sport performance, we can state that great progress has been made in the last years by using electronic measuring techniques, such as miniature counters for heart rate (*Rowley 1959, Ryan 1960*), radio telemetry of the electrocardiogram (*Bellet et al. 1961, 1962a, b; Dendal 1962; Freiman et al. 1960; Frucht and Otto 1958; Holter 1957, 1961; Ira et al. 1963; Metzner 1958; Rozenblat 1961; Schaff and Schieber 1960; Scholl 1959; Vodolazsky et al. 1961, etc.*), the electromyogram (*Saryčev 1959, 1962; Battye 1962; Gumener et al. 1963*) and similar methods.

It is useful to compare the aforementioned task of occupational medicine with problems of ecological physiology of animals. While the co-operation of the examined human subject with the research worker, the fixation of electrodes, transducers, amplifiers or transmitters, rarely represent a difficult problem in occupational medicine, they are critical for most examinations in animals, especially in those living wild. A special symposium

was devoted to this problem in 1962 (Slater, edit., 1963). – On the other hand, electrical recording of physiological functions, especially biopotentials, in the working human subject is disturbed and distorted by electromagnetic fields caused by industrial equipment and machinery. The elimination of these undesired influences usually requires special attention in the design of biomedical measuring instruments. For example, the electrocardiographic potential can be used for reliable heart rate counting after amplification with a selective narrow band-pass preamplifier, even when interference from the electro-myogram and pick-up from mains-operated machinery is larger than the EKG signal itself (Peňáz 1960, Mikiska 1962 a, c).

One of the modern electronic techniques, contributing greatly to the versatility of present physiological instrumentation, is recording on the magnetic tape, allowing writing-out or automatical analysis of the recorded data to be performed subsequently, e.g. in another laboratory. Description of the system of magnetic recording, developed in our laboratory for use in occupational medicine, was presented in our previous paper (Mikiska 1962 b), including a review of various systems as well as applications.

We have later supplemented our frequency-modulation system for magnetic recording of biopotentials with a complete preamplifier and with a simple (frequency-modulated or amplitude-modulated) radio-frequency stage, performing wireless transmission of the signal to the distance of several tens of meters (Fig. 1). Transmitters built according to this principle possess all gener-

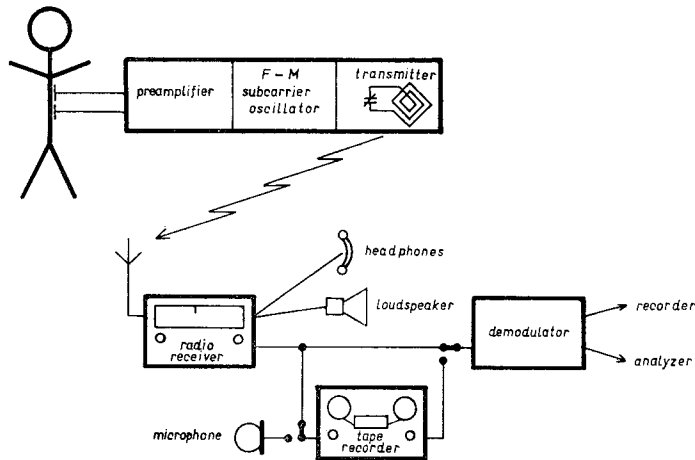


Fig. 1. Schematic diagram of the telemetry-magnetic recording system.

ally known advantages of radio telemetry (free movement of the subject, absence of galvanic connection between subject and recorder, etc.), ensuring moreover the possibility of magnetic recording.

The objective of the present paper is to describe two types of transmitters that have been tested in field research in the years 1965–1966.

## General description of the telemetry-magnetic recording system

Most simple telemetering devices can be designed by modulating the oscillation frequency of a transmitter directly by the amplified bioelectric voltage, e.g. the electroencephalogram (*Fischler et al. 1961, Fischler and Frei 1963*), the electrocardiogram (*Barry 1964, Ira and Bogdonoff 1962, Macek and Jilek 1963, Schwartz 1961, Shipton 1960*), distorted electrocardiogram for heart rate counting (*Essler and Folk 1962, Seliger and Hrdlička 1965*), summation electromyogram (*Saryčev 1959, Battye 1962, Gumener et al. 1963*), etc. – By means of voltage-dependent capacitors (“varicaps” or “varactors”), sufficient frequency deviation can be achieved even by the unamplified bioelectrical voltage, e.g. EEG (*Davidoff et al. 1962, Michael et al. 1965*). The size, weight and power consumption of these transmitters with single frequency modulation is very low; on the other hand, if the transmitted biopotential is to be reproduced without distortion of amplitude and waveform, special receivers with effective amplitude limitation must be used that eliminate completely sensitivity to amplitude modulation, caused for instance by movements of the subject.

The use of a frequency-modulated subcarrier audio-frequency, although rare in transmitters telemetering one channel of bioelectric potential only (*Gemant et al. 1956, Rozenblat 1963, Mikiska 1965, Deboo and Fryer 1965*), has many advantages for transmitters designed for research as well as routine examinations in occupational physiology:

1. If the subcarrier deviation is high enough, it is possible to record the subcarrier audio-frequency on a conventional magnetic tape recorder allowing, as has been already mentioned, to write-out and/or analyse the recorded data subsequently under more favourable conditions.

2. Simple and non-expensive devices, e.g. standard FM tuners for broadcast or superregeneration detectors, can be used for receiving the signal.

3. When the subcarrier frequency is fed from the receiver to headphones or to a loudspeaker, the pitch of the corresponding tone varies in the rhythm of the biopotential. This fact can be utilized for auditory monitoring of the telemetered signal, facilitating precise adjustment of the receiver to the frequency of the transmitter. – Auditory monitoring is of special interest when electrocardiographic voltage – undistorted or intentionally distorted by a narrow band-pass frequency filter – is fed to the transmitter submodulator. The physician can then evaluate the heart rate and regularity of the cardiac rhythm by counting the fluctuations in the pitch of the subcarrier tone, in a similar way as during auscultation of the patient’s heart tones.

Frequency modulation of the subcarrier audio-frequency is essential for achieving the advantages mentioned above. On the other hand, the carrier radio-frequency can be equally well either amplitude- or frequency-modulated, although some authors (*Rozenblat 1963, Rimslich 1963*) claim that systems with frequency modulation of the carrier are less prone to signal distortion when tuning of the receiver is not precise on the transmitter frequency.

The schematic diagram of the receiving part of our equipment is shown in the Fig. 1. Its main parts are commercially available devices (FM broadcast receiver, adapted by providing several frequency bands from 40 to 95 Mc/s,

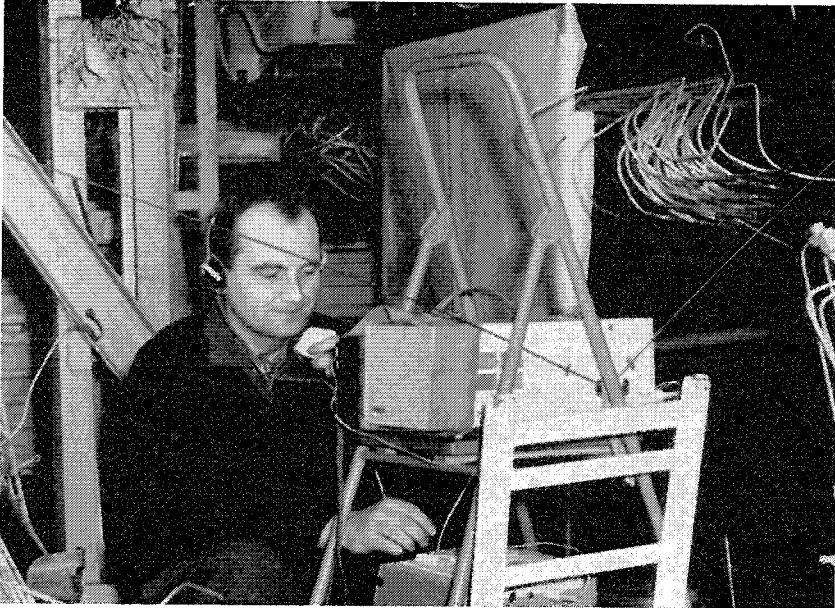


Fig. 2. Physician at the receiver and recording equipment.

and a magnetic tape recorder), supplemented by the demodulator of the sub-carrier audio-frequency, similar to that described in our paper on magnetic tape recording (*Mikiska 1962 b*).

Fig. 2 shows the experimenter (Dr. *J. Urban*) examining heart rate during industrial work. – When the only evaluation of heart rate is done by counting the fluctuations in the tone pitch of subcarrier audio-frequency, a pocket-size portable FM broadcast receiver is sufficient (adjusted, if necessary, to another frequency band).

All transmitters described in this paper operate without any transmitting antenna; the radio-frequency signal is radiated only by the coil of the oscillating circuit, by the leads to the electrodes and by the patient's body. This fact is of great importance in examination of work physiology, because it allows the transmitter to be worn under the clothes.

The placement of the radiotelemetric transmitter under the clothes has the following advantages:

1. The transmitter is protected against temperature fluctuations as well as other unfavourable factors of the work environment.
2. The hazard of electrical injury (due to accidental contact of the electrodes, electrode leads and transmitter with mains supplies or other sources of high voltage) is eliminated.
3. The transmitter and electrodes may be practically invisible to co-workers

or visitors, so that emotional stress of the experimental subject arising from medical examination is minimal.

This circumstance is especially important for neurotic subjects or patients when examined in their normal conditions of living and working.

Fig. 3 demonstrates that even the larger of our transmitters, when fixed with a broad rubber band on the worker's back under the clothes, is visible only when the subject is bent forward.

The polarization of the radio-frequency signal, radiated by the coil of the oscillation circuit, by electrode leads and by the body of the examined subject, is quite general. Therefore, in most cases any type of receiving antenna can be used. Sometimes, however, the field intensity of the horizontal component declines with the distance at a different rate than that of the vertical one. In workers employed in forestry, a larger range of telemetry was achieved with vertically oriented receiving dipole; this fact was probably due to absorption or straying of radio-frequency energy by the trees. On the other hand, in most factories, receiving with a horizontally-oriented dipole may be recommended, because the vertical component is more absorbed by conductive floors and ceilings.

Transmitters described in this paper were designed to operate in the frequency range 40 to 95 Mc/s. In most countries, the band  $40.68 \text{ Mc/s} \pm 0.1\%$  is one of those reserved for shortdistance radio-frequency transmission of various signals. Besides this, radio-frequency devices used for industrial, scientific or medical applications are not considered as radio transmitters, unless they are operated with a radiating system (antenna) or unless their radiation causes at the distance of 1 kilometer a field intensity larger than a certain limit (*Petránek 1965*). – Nevertheless, in spite of the limited action radius of the devices described in this paper the interference caused to industrial control or safety-watching systems can be sometimes quite serious: local telecommunication authorities should be therefore consulted upon these problems.



Fig. 3. Recommended fixation of the transmitter. Clothes protect the transmitter against thermal and other unfavourable factors of environment. Subject at work in a bent position, wearing the transmitter under her clothes.

## EKG transmitter

The wiring diagram of the first transmitter, designed especially for telemetering of the electrocardiogram, is shown in the Fig. 4. The amplifier consists of four stages.  $Q_1$  operates as an emitter follower (ensuring higher input impedance),  $Q_2$  and  $Q_3$  as common-emitter amplifying stages, and  $Q_4$  as an emitter follower.  $Q_5$  stabilizes the supply voltage for  $Q_1$  and  $Q_2$ , eliminating thus undesired feedback across the battery resistance.

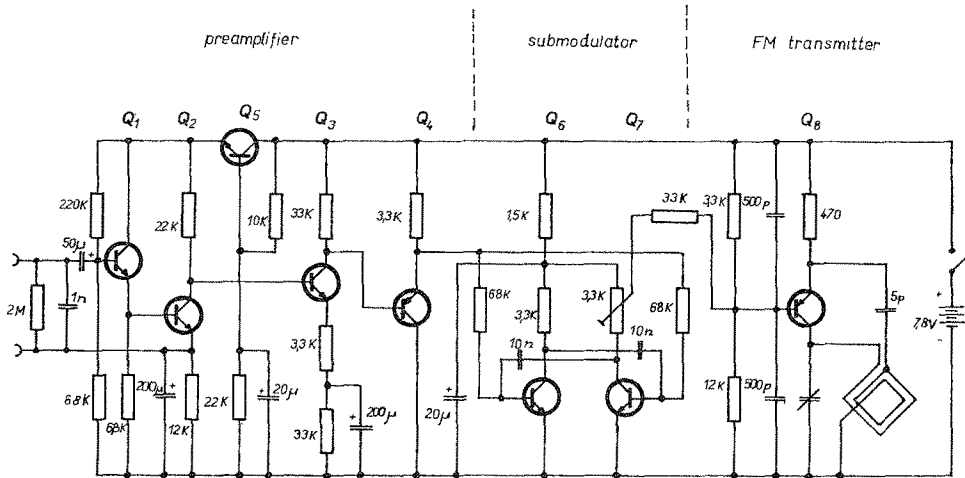


Fig. 4. Wiring diagram of the EKG transmitter.

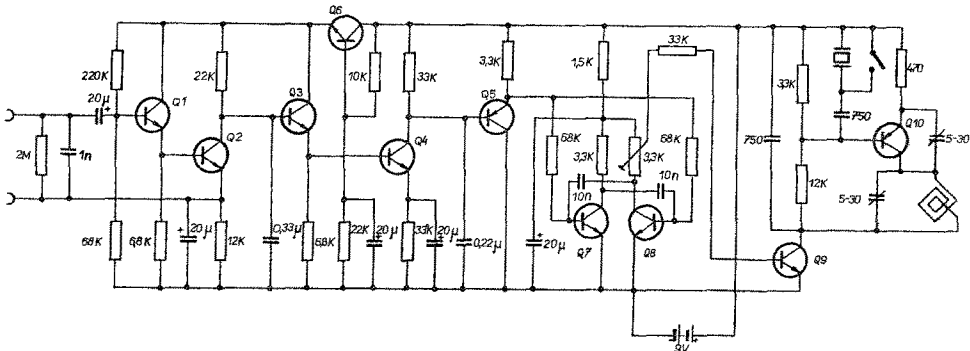


Fig. 5. Wiring diagram of the heart rate transmitter.

A loop of positive feedback is used for correction of frequency characteristic at its lower limit: the voltage dropped across the capacitor 200 microfarads in the emitter lead of  $Q_2$  is lead via the recording electrodes to the base of  $Q_1$  (i. e., it is connected in series with the input signal). This positive feedback is,

however, effective only when inter-electrode resistance is much lower than the input resistance of  $Q_1$ ; inter-electrode resistance values up to 10 kilo-ohms were found to be acceptable.

Voltage gain of the order 500, relatively high input and low output impedance as well as high stability, due to bridge stabilization of collector currents, are characteristics of this amplifier.

A symmetrical multivibrator circuit is used as submodulator, that is, a generator of a frequency-modulated subcarrier audiofrequency. The mean value of subcarrier frequency is approx. 1200 c/s; the modulation characteristic is linear in the range  $\pm 30\%$  of the mean value of subcarrier frequency, which corresponds to maximal input signal amplitude  $\pm 3$  millivolts. The linearity and stability of a multivibrator used as frequency modulator is the better the lower the zero collector currents of the transistors (*Mikiska 1962 b, Unžin 1963*); moreover, current gain should be similar for both transistors of the pair.

The radio-frequency oscillator is frequency-modulated by the subcarrier audio-frequency controlling the voltage across the collector-base junction and, consequently, the capacity collector-base. The deviation is adjusted by the potentiometer 3.3 kilo-ohms in the collector lead of  $Q_7$ .

Six mercury cells or a 9 volt battery of dry cells serve as power supply.

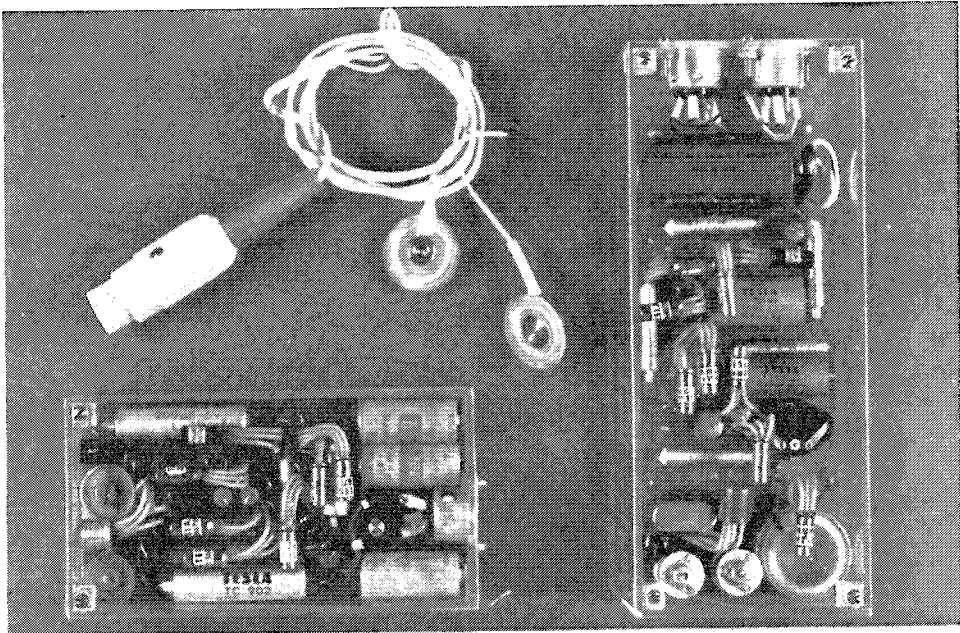


Fig. 6. External appearance of described telemetric transmitters. In addition, electrodes for fixation with collodion are shown.

External appearance and construction details are shown in the Fig. 6 (left side). Standard miniature components are used to minimize the costs for the transmitter: the device can therefore be easily duplicated and used for simultaneous examination in many subjects. The weight of the transmitter (including the battery) is approximately 160 grams; it could be still reduced by using microminiature components or integrated circuitry.

The input resistance is approximately 50 kilo-ohms. – The frequency characteristic (Fig. 7) is somewhat dependent on the impedance of signal source, i.e. on inter-electrode resistance. The frequency band (presented for attenuation – 3 dB at the band limits) is 0.5 to 160 c/s with inter-electrode resistance less than 10 kilo-ohms (full line), but only 1 to 160 c/s, when inter-electrode resistance exceeds 30 kilo-ohms (dotted line). – The upper limit of the frequency band depends mainly on the demodulator; it could be increased up to 300 c/s by the use of a more complicated demodulator circuit.

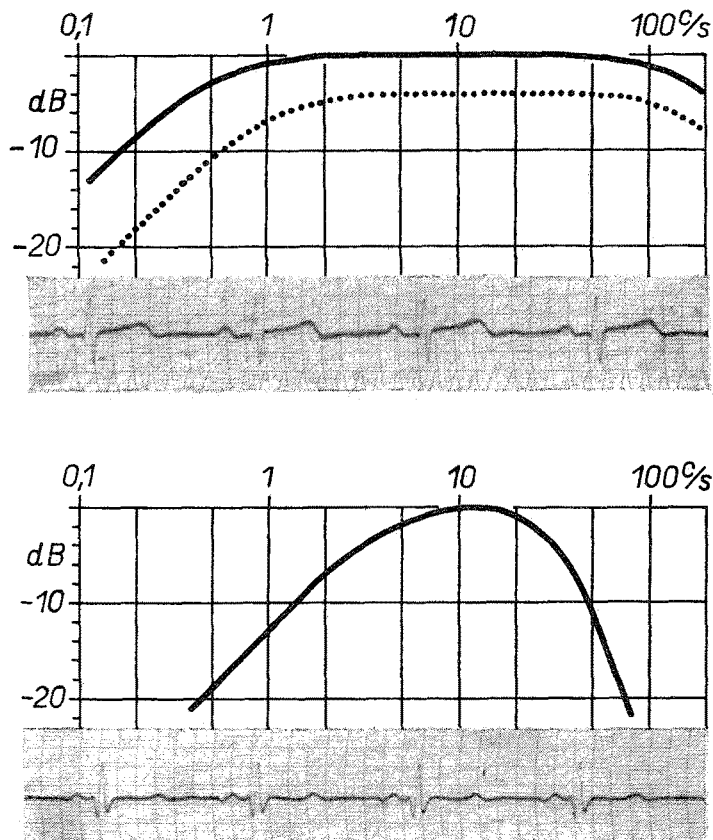


Fig. 7. Amplitude frequency characteristics and examples of telemetered records. Top: EKG transmitter. Bottom: heart rate transmitter.

As is apparent from the presented data, the EKG transmitter can be used not only for recording the electrocardiogram, but also other types of bioelectric signal, e.g. summation electromyogram.

The electromyogram, picked-up from skin electrodes applied over a reasonably selected muscle group, can provide to the occupational physiologist precise information on the rhythm of working movements, i.e. duration of actual muscular effort as well as of short "micropauses".

Under favourable open air and other conditions, telemetering of the electrocardiogram or summation electromyogram of working or exercising human subjects with the EKG transmitter is usually possible up to a distance of 70 meters; exceptionally, even over more than 100 meters. Indoors, the range of telemetry is decreased to 25–50 meters, depending primarily on the level of radio-frequency interference, caused by industrial machines in the vicinity of the subject and of the receiver.

Examples of telemetered electrocardiographic records are shown in Fig. 8. The tracings A, B, and C were obtained indoors, at a distance of 15 to 25 meters, in a male subject with silver disc electrodes, attached to the skin over manubrium sterni and heart apex<sup>1</sup> by collodion; construction of these electrodes is demonstrated in Fig. 6. – Tracing A during quiet walking is quite undistorted.

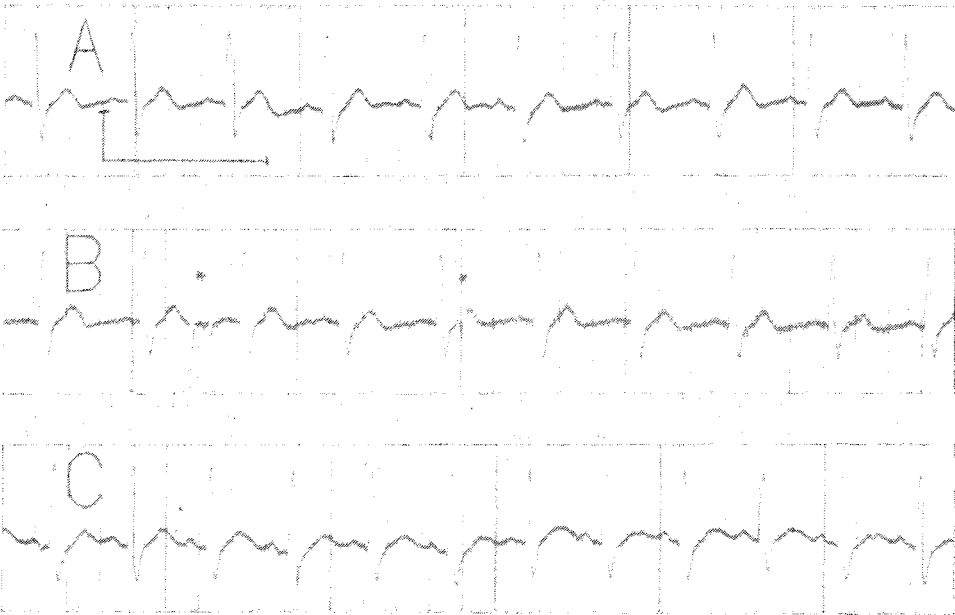


Fig. 8. Examples of telemetered EKG during rest, work and exercise.

<sup>1</sup> This localization of EKG electrodes, closely similar to the "anterior" lead according to *Nehb* (1938), was recommended for occupational physiology by *Vodolazsky, Podoba and Solovyeva* (1961).

Tracing C, recorded during squatting, shows some superimposed electromyographic activity. Tracing B, recorded during soldering with an ungrounded mains-operated soldering iron, is disturbed only in instants of switching on or off the soldering iron: this interference by sparkling is marked by asterisks.

### Transmitter for telemetering information on heart rhythm

The second type of transmitter was designed specifically for examination of heart rhythm in human subjects during work or exercise. Its wiring diagram is shown in Fig. 5.

The amplifier differs from the one used in the EKG transmitter by higher voltage gain (due to insertion of one emitter-follower stage  $Q_3$  more) and narrower frequency band (due to smaller values of capacitors shunting the resistors in emitter leads as well as to capacitors  $0.33 \mu\text{F}$  and  $0.22 \mu\text{F}$  shunting collector resistors of  $Q_2$  and  $Q_4$ ).

A symmetrical multivibrator, identical with that of the EKG transmitter, is used as submodulator.

As far as heart rate measuring can be performed also in subjects during gross body movements, the performance and versatility of the transmitter was increased by a more complicated circuit of the radio-frequency oscillator.

When the contact, shunting the quartz resonator, is switched off, the oscillation frequency can be stabilized at the value of  $40.68 \text{ Mc/s}$ , the third harmonic frequency of the piezoelectric resonator; the radio-frequency oscillations are amplitude-modulated and the depth of modulation can be varied from zero to 100 per cent by the potentiometer in the collector lead of  $Q_8$ .

When the quartz resonator is short-circuited, the oscillator can be tuned to any frequency up to approx.  $95 \text{ Mc/s}$ . Depth of amplitude modulation is now to be adjusted only to several per cent: changes in the capacity collector-base result under these circumstances in satisfactory frequency modulation of the radio-frequency carrier (deviation of several tens of  $\text{kc/s}$ ) that can be easily detected by standard FM-radio receivers.

External appearance of the heart rate transmitter is shown on the right side of Fig. 6. A larger coil of the oscillation circuit (3 turns of flexible cable on a plexiglass former with diameter 17 mm:  $L = \text{approx. } 0.3 \text{ microhenry}$ ) provides more effective radiation of the radio-frequency energy: the signal is easily received in open air over more than 100 meters. The total weight of the transmitter with battery is approximately 250 grams.

The input impedance is approximately 50 kilo-ohms. The amplitude frequency characteristic is shown in Fig. 7: attenuation of voltage gain – 3 dB is reached at band limits 4 and 30 c/s. – This frequency response accentuates in the human electrocardiogram the complex QRS against slower waves P

and T: in Fig. 7, this fact is demonstrated by examples of tracings, recorded by both types of telemetric transmitters. (Tracings in Fig. 7 were recorded in a female subject with collodion fixed electrodes, placed over manubrium sterni and processus xiphoides, the EKG lead, proposed for exercising subjects by *Geddes et al.* in 1960.)

The heart rate transmitter effectively reduces many types of artefacts, disturbing or even completely masking the electrocardiogram, characterized either by slow potential fluctuations (e.g., movement artefacts or galvanic skin reactions) or by frequency components in the range of several tens of c/s (e.g., electromyographic potentials or mains pick-up). Possibility of detecting information on cardiac rhythm from the electrocardiogram grossly distorted by interference was in more details discussed elsewhere (*Peňáz* 1960, *Mikiska* 1962 a, c, 1965): summing up, we can state that the use of a narrow band pass filter is effective in most types of human work in industry and agriculture.

The possibility of reducing interference of various origin enables the heart rate transmitter to be connected also to less perfect electrocardiographic electrodes, e.g. attached by a rubber band (*Mikiska* 1962 a) or by adhesive tape. The transmitter is therefore suitable for routine examination of heart rate in occupational physiology, sport medicine and related branches.

Auditory monitoring of the subcarrier audio-frequency by the experimenter (listening to the sound signal of the receiver and counting the heart systoles) enables immediate continuous watching of the heart rate, making thus often unnecessary the use of a recorder.

### Final remarks

Up-to-date, six transmitters were built according to principles described in this paper: two for telemetering the EKG, four for transmitting information on the heart rhythm.

The operation of transmitters is stable in the temperature range  $-5^{\circ}$  to  $+35^{\circ}$  C. – With a 9 volt battery and carrier frequency modulation, current drain varies from 7 to 9 milliamperes, depending slightly on the value of transmitted radio-frequency. The total power consumption is, consequently, 60 to 80 milliwatts. Output power of radio-frequency is approximately 30 milliwatts, from which, however, only a small fraction is actually radiated by the oscillation circuit coil, the electrode leads and the patient's body. – When the radio-frequency is stabilized by the quartz resonator and carrier amplitude modulation is used, the power output as well as power consumption are decreased the more, the deeper the modulation.

Types of transistors, used in the circuits, are indicated in a following table. N-p-n germanium transistors were used in most stages because their values of

collector rest current are lower than for corresponding p-n-p types. Nevertheless, similar circuits can be constructed entirely from p-n-p transistors, e.g. AC 150, in the amplifier and multivibrator stages. The respective wiring diagrams may be sent by the author on request.

Radiofrequency energy radiation of the heart rate transmitter was estimated for carrier frequency modulation in the band 66 to 73 Mc/s: there were found values ranging about  $0.05 \mu\text{W}$  with an artificial signal generator, but  $0.3\text{--}1 \mu\text{W}$  during actual operation when radiation was increased by electrode cables and the patient's body.

*List of semiconductor components*

		EKG transmitter	heart rate transmitter	equivalent
Alloyed-junction transistors				
n-p-n low-frequency, low-noise type	107 NU 70	$Q_1, Q_2$	$Q_1, Q_2$	
n-p-n low-frequency, all-purpose type	107 NU 70 102 NU 71	$Q_3, Q_5$	$Q_3, Q_4$ $Q_6, Q_9$	OC 140 OC 141
n-p-n high-frequency type	156 NU 70 matched pair	$Q_6, Q_7$	$Q_7, Q_8$	
p-n-p low-frequency, all-purpose type	OC 72 OC 76	$Q_4$	$Q_5$	OC 72 OC 76
Diffused-base transistors				
p-n-p	OC 170 OC 171 AF 115 AF 116	$Q_8$	$Q_{10}$	OC 170 OC 171 AF 115 AF 116

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Address of author: *Aloš Mikiška*, Institute of Industrial Hygiene and Occupational Diseases, Srobarova 48, Prague (Czechoslovakia)