The change of blood pH during exercise has been studied by many investigators but the results are conflicting not only on magnitude but also on the direction of the change. As pointed out by MATELL, the major reason which causes the inconsistency is that these data were obtained by spot-sampling techniques.

Recently, several methods to record the change of blood pH have been reported, but in these methods, blood samples were led to the electrodes by catheters. The authors have devised the pH glass electrode which is implantable into blood vessels of experimental animals so as to perform continuous recordings of pH of circulating blood in situ. The E.M.F. of the pH glass electrode implanted in the experimental animal was applied to radiotelemetry, and the pH of circulating blood of animal running on the ground was recorded on the polygraph which is placed in the laboratory.

In this paper, the construction of the implantable pH glass electrode and the method of its radiotelemetry are described, and their applicability is discussed.

METHODS

I. Implantable pH glass electrode. The construction of the electrode is schematically illustrated in Fig. 1. The pH glass electrode is composed of a pH sensitive Li glass membrane (pH glass in the figure), and the electrode shaft (Pb glass) and an inner reference electrode (Ag-AgCl electrode). The inner solution of the electrode is the phosphate buffer which is about 7.40 pH and is mixed with 0.1 M potassium chloride solution to provide Cl ion the reference electrode. In order to fix the inner reference electrode to the electrode shaft, Araldite (CIBA) was used as insula-

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CONSTRUCTION OF pH ELECTRODE

FIG. 1. The construction of an implantable pH glass electrode.
(A) pH glass electrode. (B) Implantable pH glass electrode assembly.

tion material to obtain a high insulating resistance. A small air bubble was included in the electrode shaft to avoid the destruction of the glass membrane due to expansion of liquid volume by a temperature rise. Another Ag-AgCl electrode is applied to the external wall of this pH glass electrode as the outer reference electrode and is fixed with a silicon rubber ring moistened with 3 M KCl solution so as to maintain electrical conductivity.

The electrode assembly thus constructed was inserted into the central opening of a T tube (Fig. 1-B) and was fixed with high insulating ceresin wax to the wall of a T tube. The animals used were mongrel dogs. The dog was slightly anesthetized with barbiturate, and the T tube was implanted into the carotid artery under the skin. When this electrode is applied to such a blood vessel as pulmonary artery, the insertion of the electrode may hinder the blood circulation. In this case, the electrode assembly (pH glass electrode and outer reference electrode) may be inserted from a side branch of the pulmonary artery without using a T tube.

II. Radiotelemetry. FM-AM system was applied as the telemetering system. The block diagram is shown in Fig. 2 and the circuit diagram of the meter in Fig. 3. The technical difficulty which is encountered in constructing the telemetering transmitter is the high inner resistance of the pH glass electrode which is of the order of 50 M ohms. Thus, the input impedance of the meter should be taken high enough. At the present time, however, both a high input impedance of the preamplifier and a high stability of the meter can not be obtained by using commercially available semiconductors. As the chopper system needs driving power oscillator of high weight and power, it is not suitable for our experiment in which the meter is to be carried by
the experimental animal. Accordingly, a subminiature tube 5886 was used as the impedence converter (preamplifier). The E.M.F. of the pH glass electrode is amplified, after impedance conversion, about 46 db (approximately × 500) by two differential amplifiers using a twin transistor pP 15 and a pair of 2SB77. The amplified E.M.F. is applied to the base circuit of an astable multivibrator to obtain FM wave whose output frequency is proportional to the applied voltage.

The characteristics of the meter are as follows: the output frequency is shifted by 30 cps with 1 mV of input to the first stage or 180 cps per 0.1 pH change. Twenty seven Mc main carrier is oscillated with a crystal oscillator which is modulated by the rectangular wave from the astable multivibrator. The first stage of the amplifier and high frequency parts are separately shielded with copper plate to protect the parts from induced noises and to avoid the effect of radio frequency wave on the adjacent circuits. A rigid ferrite bar antenna (8 x 150 mm) is adopted to prevent the noise by body effects caused from movements of the antenna. Two 1.3 V mercury
cells are used as the heater cells of subminiature tube 5886. A power pack of 27 V whose output is stabilized with 2SB81 from seven 6 V dry cells is used as a B source. The dimension and weight of the meter is 18.5 × 9.0 × 4.0 cm and 800 g respectively. The power pack measures 15.0 × 10.0 × 5.0 cm and weighs 750 g. Both of them are fixed to a belt which is firmly tied to the trunk of a dog.

As receiver, super-heterodine system (RF: 1, IF: 2, Bandwidth: ±3 Kc.) was employed. The detector output was applied to rate meter through pulse shaper and the output of the rate meter was recorded with pen recorder (Miniploygraph; GME).

RESULTS AND DISCUSSION

I. Implantable pH glass electrode. Fig. 4 shows the responses of the pH glass electrode to several buffer solutions of which the pH range is 4 to 9. Among these, three standard buffer solutions of which pH was 4.01, 6.86 and 9.18, respectively, were prepared according to NBS standard4), and two phosphate buffer solutions of 7.42 and 7.55 pH were prepared according Sörensen5). The electrode potentials were plotted in Fig. 4 against the known pH values of standard buffer solutions. It is demonstrated that a good linearity exists between pH and E.M.F. of the glass electrode. The slope of the regression line is close to 58 mV per one pH unit which is almost equal to Nernst's theoretical value for 25°C. The electrode potential which was obtained by measuring one of the buffer solutions was constant within 1 mV for several hours. The standard deviation calculated from the electrode potential which was determined repeatedly with one and the same buffer solution was within 1 mV.

To obtain a stable potential, however, it was most important to use a
stable Ag-AgCl electrode. Careful attention was paid in constructing this electrode. Ag-AgCl electrodes thus constructed should be checked for their stability before use, and in our experiment only those which showed a high stability (a drift within ±0.5 mV over 5 to 6 hours) were used. In order to construct an Ag-AgCl electrode, Pt wire of 0.5 mm bore was fused in a glass tube and was plated electrolytically with Ag in AgNO₃ solution. This Ag electrode was chlorinated electrolytically to form an AgCl film over Ag plated. Then the AgCl powder was pasted over the AgCl electrode and was fused with a micro-burner. These electrodes are very resistant mechanically against rubbing off and can present a stable potential.

Response time of the pH glass electrodes was fast enough to complete within the time required for the movement of recorder's pen. However, it was found later that this electrode has serious source of error in precise quantitative analysis of acid-base balance in blood while it is applicable to detect changes in blood pH. Details of this source of error will be discussed elsewhere.⁷

In order to verify the applicability of this electrode, some experiments were performed on dogs weighing 8 to 15 Kg. A part of the experimental records is shown in Fig. 5. Under general anesthesia with Tiopental Sodium (25 mg/Kg of body weight), a carotid artery, the thrachea and a femoral vein were exposed. After careful ligation of the bleeding site, Heparin (1,000 μ per Kg of body weight) was injected through the femoral vein. After the injection of Heparin, a T tube with a pH glass electrode was inserted into

Fig. 5. An example of the experimental records.
Upper tracing is a respiratory frequency curve recorded with the circuit which is shown in left half of the figure. About the details, see the text.
the carotid artery so as to make blood flow through the T tube and fixed there by ligatures. The electrode part is covered with muscles and connective tissues there and maintained at body temperature. At the same time, the trachea was cut to insert a tracheal catheter, to which a thermistor was fixed to record a respiratory frequency curve. In recording both arterial blood pH and respiration, 10 cc of N/0 HCl was injected through a femoral vein. The pH change of carotid arterial blood and change of respiration initiated by the acid injection are illustrated in Fig. 5.

With the above technique, the authors studied the chemo-receptor which plays an important role in muscular exercise. The study will be reported elsewhere.

II. Radiotelemetry. The characteristics of the telemetering system are illustrated in Fig. 6, which shows the relationship between the input voltage and

![Graph](image.png)

**Fig. 6.** A chart illustrating characteristics of the telemetering system.

Output frequency of the receiver (open circles) and output voltage of the rate meter (closed circles) are plotted against input voltage to the meter indicated by a small circle in Fig. 2 and 3.
the output frequency of receiver or the output voltage of rate meter. As shown in the figure, the sensitivity of the telemetering system is 30 cps/mV or 180 cps/0.1 pH. As drift appears in the range of ±10 to ±50 cps, the pH measurement is possible with the accuracy of 0.01 to 0.05 pH. A linear relationship exists between the output frequency and the input voltage in the range of −25 to +25 mV. It follows that the telemetry of about 1 pH change is possible with good linearity.

As to advantages of this FM-AM system, it can be pointed out that a highly stable telemetry is possible with a conventional AM receiver.

In order to apply this technique to an exercising dog, a carotid artery was opened under a light general anesthesia with Thiopental Sodium and local anesthesia with Xylocain. Each bleeding site was ligated carefully and Heparin (1,000 u/Kg of body weight) was administered intravenously. After cutting the carotid artery, the two ends of the T tube were inserted into the cut ends of carotid artery, respectively, and the pH glass electrode was tightly fixed to the artery and then the skin of the operation site was closed. The lead wire of the electrodes was fixed to the skin so as to avoid any movement of the pH glass electrode. After recovering from the effects of anesthesia, the dog was allowed to walk or to run, and the pH change was recorded.

One of the records obtained by this technique is shown in Fig. 7. Large

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**Fig. 7.** One of the telemetered records of blood pH from a dog which is exercising outside the laboratory.

The dog is in a recumbent state at the upper tracing, walking during the recording of the middle curve and is running for several minutes during the recording of the lowest curve indicated by the arrows. The scale of pH change is shown by a vertical line.
spike-like peaks are records of noise due to jamming waves from outsides and small ones are due to strong agitations of the meter, but it can be observed that the fluctuation of arterial blood pH appears dominantly during walking states, while it appears very little during the recumbent states of the dog. When the dog starts to run, the arterial blood pH shifts to the alkaline side gradually at first and then it turns to the acidic side after the end of the exercise. The authors verified the same results in another experiment in which the implantable pH glass electrode was connected to a pH meter, and a recorder which was placed in the center of circular course of the running dog. The details of the experiments will be reported elsewhere.

The present meter is somewhat too large in size and its sensitivity is low. Improvements are, however, being made in many respects and will be reported in the future.

SUMMARY

Implantable pH glass electrode for continuous recording of blood pH in situ is described. The electrode was applied for telemetering of pH of circulating blood in running dogs.

Results obtained are as follows:
1. This pH glass electrode gave 58 mV per one pH change which almost satisfy Nernst's theoretical value.
2. The stability of the electrode was high (within 0.017 pH units over several hours) and the reproducibility was very good (±1.0 mV of standard deviation).
3. Response time of the electrode was fast enough to detect rapid change of blood pH.
4. Radiotelemetry of blood pH was attempted with this pH glass electrode by FM-AM system. The telemetry gave fairly stable and reasonable results.

REFERENCES