

Technical report

Measurement of digestive variables in free-living animals: gastric motility in penguins during foraging

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(Received July 28, 2003; Accepted July 28, 2003)

Abstract: A stomach motility probe was developed in order to investigate digestive regulation in penguins. The sensor was a piezoelectric PVDF film which generated a voltage according to the extent and the speed at which the film was bent. This gave an estimate of the intensity of the contraction waves. Since measurements over periods of several days under natural conditions were necessary for the study, a data logger was used for data acquisition. The whole unit, incorporated in a titanium tube, was fed to the penguins and allowed measurement in free-living animals. Since it was not considered necessary to detect every single contraction wave but rather to get an overall picture regarding the phases of high or low stomach churning, the sensor was coupled to a voltage integrator with a free-adjustable time constant. This setup allowed the signals of one or several contraction waves to be summed. The data were stored in a two-channel data logger with 8 bit resolution and a memory of 128 kB. The logging interval was programmable. The second channel was used for recording the temperature to provide information about the feeding behaviour of the animals.

key words: digestive regulation, telemetry, data logger, stomach temperature, thermoregulation

Introduction

In gastric digestion there are some basic processes which determine the rate at which stomach contents are digested. Apart from secretion of enzymes and HCl, peristalsis mixes the food with gastric juice and transports it through the alimentary canal. Knowledge of the gastric motor activity provides information on the actual state of digestion (Kostuch and Duke, 1975) and allows evaluation of potentially influencing factors such as *e.g.* diet (Wilson *et al.*, 1985; Jackson and Ryan, 1986), nutritive status (Clench and Mathias, 1992), ontogenesis (Karasov, 1990), environmental effects and season (Wilson *et al.*, 1989; Levey and Karasov, 1992), or stress (Barquist *et al.*, 1992).

With the exception of radiography (Dziuk and Duke, 1972; Kostuch and Duke, 1975; Duke *et al.*, 1989) and myoelectric measurements (Duke *et al.*, 1972; Clench and Mathias, 1992) most techniques for measuring gastric motility are based on sensing intraluminal pressure (ILP) changes effected by peristalsis. This is done by either introducing compressible

balloons (Mangold, 1906; Appert *et al.*, 1971; Heller *et al.*, 1986) or fluid-filled tubes (Duke and Evanson, 1972; Camillereri *et al.*, 1985) connected to pressure gauges outside the body. In addition ILP has been measured telemetrically using pressure transmitters (Kostuch and Duke, 1975). A different approach to the study of gastric motility is to monitor the movements performed by the stomach wall during peristalsis, rather than measuring the pressure wave. This latter technique has been used by Kuechle and co-workers on owls, where strain gauge transducers were employed and data were transmitted telemetrically (Kuechle *et al.*, 1987).

Here, I present a new device for monitoring gastric motility in free-ranging animals. It was developed to study digestive regulation in penguins and has meanwhile been used in a range of other seabirds and in cattle. The autonomous stomach probe works independent of ambient pressure and independent of a base station and as such has an unlimited spatial range of operation.

Material and methods

Since ILP measurements could not be performed in diving animals, direct detection of stomach motion was chosen as the most suitable method for monitoring gastric motor activity.

A piezoelectric PVDF (polyvinylidene difluoride) film was employed as a sensor (Type LDT1-028K, film size 12.5×30 mm; AMP Piezo Film Sensors, Valley Forge, PA 19482, USA). This material generates a voltage according to the extent and the speed at which it is bent (*cf.* Amato, 1989). This provided the possibility of monitoring not only the number of contraction waves but also their intensity.

Since it was not considered necessary to describe every single contraction wave in its exact course but rather to get an overall picture regarding the phases of high or low stomach churning, the sensor was coupled to a voltage integrator with a free-adjustable time constant, controlled by a microprocessor and a low power real-time-clock (IDE, Hamburger Chaussee 53, D-24113 Kiel, Germany). This setup allowed the signals of one or several contraction waves to be summed, depending on the length of time over which signals were sampled before storing. This feature, together with the use of exchangeable capacities, being part of the integrator, facilitated adjustment of the system sensitivity to the prevailing conditions. As the sensor generated a positive as well as a negative voltage, depending on the direction of bending, a filter was incorporated to allow only one signal quality to be processed.

Since measurements over periods of several days under natural conditions were necessary for the study, a data logger was used for data acquisition. The data were stored in a two-channel 128 kB EEPROM-logger with 8 bit resolution (IDE, Hamburger Chaussee 53, D-24113 Kiel, Germany). The logging interval was freely programmable. The second channel was used to record the temperature so as to provide information about the feeding behaviour of the animals (*cf.* Wilson *et al.*, 1995).

The logger was placed in a pressure-tight titanium tube with the piezo sensor protruding through a slit in the cap. The piezo sensor was provided with an epoxy bulb at its distal end and coated with a layer of silicone rubber to protect it from aggressive gastric secretion and to prevent it scratching the gastric mucosa (Fig. 1). The temperature sensor (PT 1000) was attached to the anterior tube wall adjacent to the piezo sensor.

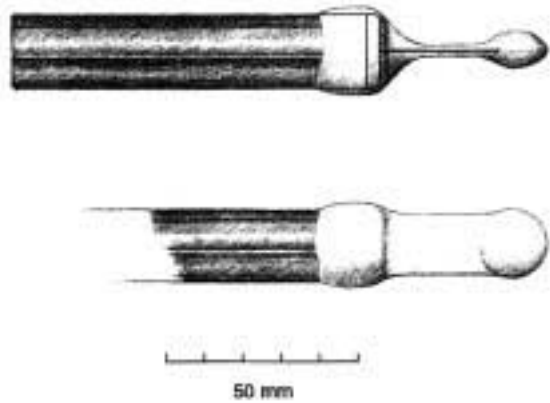


Fig. 1. SMT-probe in side and top view. In some instances, in order to reduce the risk of regurgitation, the titanium housing incorporating the electronics was equipped with a non-corrosive spring-crown (cf. Wilson *et al.*, 1998).

The stomach motility/temperature probe (SMTP) was 140 mm long (including sensor), 19 mm in diameter and had a mass of 45 g. The probes were fed to breeding penguins (*Spheniscus magellanicus*, *Pygoscelis adeliae*, *P. papua* and *P. antarctica*) with the sensor pointing towards the stomach entrance when in place. Instruments were left in the birds for up to 8 days after which they were recovered by stomach flushing (according to Wilson, 1984) or by use of a special retrieval loop (Wilson *et al.*, 1998).

In some birds, diving activity was monitored in parallel (unpublished data, Peters *et al.*, 1998) to provide information about the foraging performance of the animals under study.

For comparison, and to achieve an estimate of the temporal resolution of the system, additional ILP-measurements were performed while birds were on land. For this a logging unit with a pressure transducer (Driesen und Kern GmbH, Am Hasselt 25, D-24576 Bad Bramstedt, Germany) was given to penguins that had already earlier received a SMTP. These ILP-probes (ILPP) with a pressure range from 0.675 to 0.15 MPa (absolute; *i.e.* up to about 500 mbar above atmospheric pressure) had a resolution of 325 Pa (3.25 mbar) and sampled data at a fixed rate of 4 s⁻¹ with a total operating time of almost 9 h.

Results

In all cases ($n=17$), instruments were located at the base of the muscular stomach with the sensor projecting into the glandular part of the stomach (determined by a metal detector). In all deployments, probes worked reliably and the sensors never failed, even after repeated use in different animals.

A logging interval and time constant of 10 s each proved to be optimal in this application. With this standard setting, the system was capable of detecting signals with a frequency of up to 3 min⁻¹. In comparison, the SMTP-data reflected the gross pattern that was obtained by ILP measurements (Fig. 2).

Frequencies of stomach peristalsis as obtained by SMTP measurements were correlated with those obtained from ILP measurements, following a function $f(x)=a+bx^2+c\exp(-x)$ when fitted (Fig. 3). On average, there was systematic overestimation of very low frequencies and underestimation of higher frequencies in measurements performed with SMTPs (theoretically, not more than 3 contractions min⁻¹ could be detected with SMTPs due to the sample rate chosen). Frequencies around 1.7 contractions per minute were best detected.

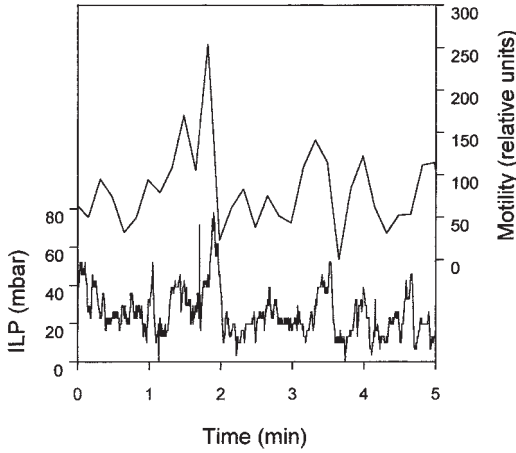


Fig. 2. Comparison of gastric motility patterns in a Chinstrap penguin *Pygoscelis antarctica* (during chick-feeding) obtained from SMTP measurements and ILP measurements. SMTP-data are displayed as relative units for a time constant of 10 s (actual units would be in V sec but the respective dimension would be dependent on the time constant and capacity used).

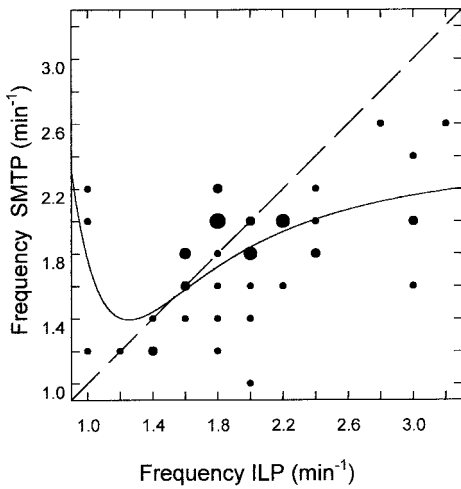
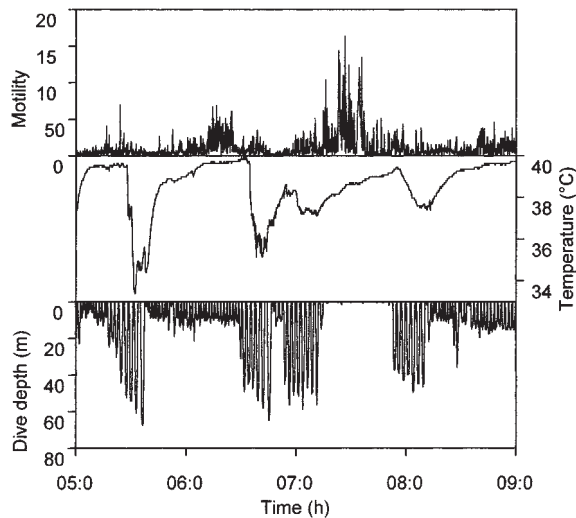


Fig. 3. Correlation between the frequency of gastric contractions in a Chinstrap penguin *Pygoscelis antarctica* detected with SMTPs and ILPPs. Frequency was determined in intervals of 5 min over 4 h ($n=48$). Symbol size reflects the different number of observations for respective pairs of data (1 to 5). The curve was fitted following an equation of the form $f(x) = a + bx^2 + c \exp(-x)$.

Fig. 4. Registration of gastric motility, gastric temperature and diving activity in a breeding Adélie penguin, *Pygoscelis adeliae*. Feeding occurred only during deep dives as indicated by drops in gastric temperature. During times of shallow diving or during a surface pause there was increased stomach motility.



Frequencies most often occurring, ranged from 1.7 to 2.2 min⁻¹ (median for ILP-measurements: 1.9 min⁻¹), whereas during chick-feeding frequencies of up to 4.9 regurgitations per minute were detected by ILP measurements (unpublished data).

Stomach motility data from birds at sea were highly variable. Parallel registration of diving activity revealed that motility was frequently reduced during diving (Fig. 4).

Discussion

Methods for sensing ILP are uniquely applicable to land-living animals and could not be used in foraging penguins since the ILP would have been superimposed by pressure changes incurred during diving and would have needed fine temporal resolution for detection. Furthermore, the high ambient pressure during diving would destroy the kind of sensitive transducers needed for ILP measurements. Therefore, the piezoelectric sensor was chosen because of its practical independence from ambient pressure (pressure changes during diving were too small and too slow to be detected by the sensor type in use). Compared to strain gauge transducers, the piezo sensor moreover has the advantage of performing an auto-zero following each motion. Thus, a defined position of the sensor is not a prerequisite for an accurate measurement as is the case in strain gauges which maintain a fixed resistance according to their curvature.

Since foraging penguins spend much time underwater, a radiotelemetric device could not be used in this study. Thus, a data logger had to be employed. Nevertheless, the logger had two shortcomings, the first being its larger size compared to pressure transmitters (*cf.* Kostuch and Duke, 1975) and the second being the limited number of signals that could be stored. For this reason I had considered not recording the stomach motion itself, which necessitates high temporal resolution, but rather measuring the effect of such a motion on a sensing element, with the additional possibility of summing signals in order to increase the archival capacity for extended periods of operation.

Although there was a systematic overestimation of low-frequency signals and underestimation of high-frequency signals (Fig. 3), this method yielded a good estimate of the grade of gastric motility. The observed differences in the signals obtained from ILPPs and SMTPs, being mainly a result of the different temporal resolution of the two systems, might have also been influenced by the different qualities of ILP changes. Not every ILP change must necessarily effect a measureable motion due to the different functions of ILP changes, such as mixing, transporting and compacting gastric contents (Kostuch and Duke, 1975).

In foraging penguins, different phases with either higher or lower stomach motility could be distinguished (Fig. 4). In particular, during phases of shallow diving or during surface pauses, the gastric activity increased, whereas activity was reduced during deep dives, indicating the birds' ability to regulate digestion. This mechanism might enable the birds to save energy in order to optimize dive performance.

Furthermore, gastric motility proved to have a massive influence on the temperature of gastric contents (unpublished data). Heat transfer from the stomach tissue to intraluminal contents is partly regulated by the extent of gastric churning and thus the extent of convective heat transfer. This might be of significance for thermoregulation in these birds feeding on cold prey, because the stomach, resembling a part of the bird's 'surface', is not insulated. Reduced gastric churning along with maintaining gastric contents cool may further help to

preserve food that needs to be brought back to the colony for chick provisioning.

Acknowledgments

This work was partly supported by the Deutsche Forschungsgemeinschaft (DFG-Ad 24/11) and the Volkswagen-Stiftung (Az I 70/122). I thank D. Adelung and R. Wilson for their advice and support, B. Guminski and T. Carstensen from IDE for helping realizing my ideas, M. Kierspel and D. Grémillet for their help in the lab and J. Regel, S. Laurenti, A.J. Scolaro, J. Upton and H. Gallelli for help during field work. Thanks are further due to R. Wilson and Y. Le Maho for improving the manuscript. This paper is based on a talk presented at the 5th European Conference on Wildlife Telemetry in Strasbourg in 1996.

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