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# Energy harvesting for active implants: powering a ruminal pH-monitoring system

**Abstract:** Energy harvesting is a feasible method to prolong service life of implanted devices. We present a thermal energy harvesting approach for a ruminal pH-monitoring probe in cattle. Thermoelectric generators utilize the temperature gradient between the probe and the ruminal fluid during water intake. The *in vivo* experiment yielded a maximum electric power of 32  $\mu$ W.

**Keywords:** energy harvesting; *in vivo*; bovine ruminal pH-monitoring

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## 1 Introduction

Most active implantable medical devices are powered by either primary or secondary batteries. Although these technologies are continuously advancing and both power density and capacity are improving, battery depletion entails loss of function or pre-emptive replacement surgery with all associated risks for the patient [1–4]. Energy harvesting is a feasible solution to render battery change unnecessary and to prolong service life of implanted devices [5–7]. It becomes even more interesting in cases where replacement surgery is impractical.

Continuously monitoring temperature and pH of the bovine ruminal fluid allows early detection of feed-related diseases [8, 9]. Ruminal pH-monitoring systems are used in large livestock to improve feed efficiency as well as animal health, but most importantly to increase milk yield and quality in dairy cows [10]. For this purpose a pH-measuring bolus is applied orally to the reticulorumen of each chosen indicator animal. The bolus can only be recovered after slaughter. Thus energy harvesting is desirable to ensure the coverage of the animal's entire productive life span.

The conditions in the reticulorumen of cattle offer a multitude of approaches to energy harvesting: Firstly, the reticulorumen of adult cattle, in which protozoa, bacte-

ria, and fungi macerate the forage under anaerobic conditions, has a capacity of approximately 200  $\ell$ . The ruminal fluid contains considerable amounts of electrolytes and short-chain carboxylic acids at an average pH of 6.4. Thus harvesting chemical energy using concentration gradients across a membrane is possible [11]. However, the huge amount of particles and microorganisms impair the membrane rapidly. Secondly, the reticuloruminal motility allows an intense mixing of the digesta, the eructation of the rumen gases, and the regulated further transport of the digesta into the omasum. In a healthy animal it varies from 0.5 contractions per minute in rest to eight contractions per minute during feeding [12, 13]. So, kinetic energy can be harvested and electric power generated up to 8  $\mu$ W [14]. Thirdly, the core body temperature of a healthy cow is 39 °C. Dairy cattle take in up to 150  $\ell$  of water per day usually with 5 to 8  $\ell$ /min, maximally 25  $\ell$ /min [15, 16]. In this study temperature gradients in the reticulorumen caused by trough water are utilized to harvest energy using the Seebeck effect.

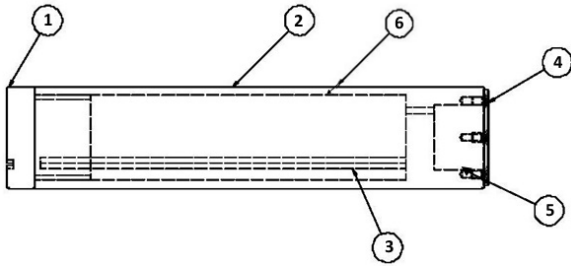
## 2 Methods

A prerequisite for this method of energy harvesting is trough water colder than the core temperature of the animal. In the reticulum a much higher temperature gradient may be observed than in the rumen due to the reticulum's smaller size and its situation between oesophagus and rumen. Placing temperature sensors in reticulum and rumen of a cannulated cow for six days a maximum temperature drop of 5 K and 1.5 K, respectively, was observed while drinking water of 10 °C.

The ruminal bolus, shown schematically in Figure 1, is a polyoxymethylene (POM) cylinder of 170 mm length and a diameter of 30 mm both ends covered with POM caps of 2 mm thickness. Into this housing was implemented a stack of three thermopiles TEC1-3104 in series circuit. A copper plate (22 mm  $\times$  22 mm  $\times$  5 mm) served as a thermal bridge between one cap and the thermopiles. Additionally a weight was integrated into the bolus to increase density above 1.5 g/cm<sup>3</sup> ensuring retention in the reticuloru-

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men. As a positive side-effect the heat capacity increased as well.



**Figure 1:** Design of the ruminal bolus (1 cap, 2 POM body, 3 weight, 4 cap and copper plate, 5 thermopile, 6 room for data logger).

The heat differential between the cooled ruminal fluid and the ruminal bolus, which has the body core temperature of 39 °C, generates a direct current in the integrated thermopiles.

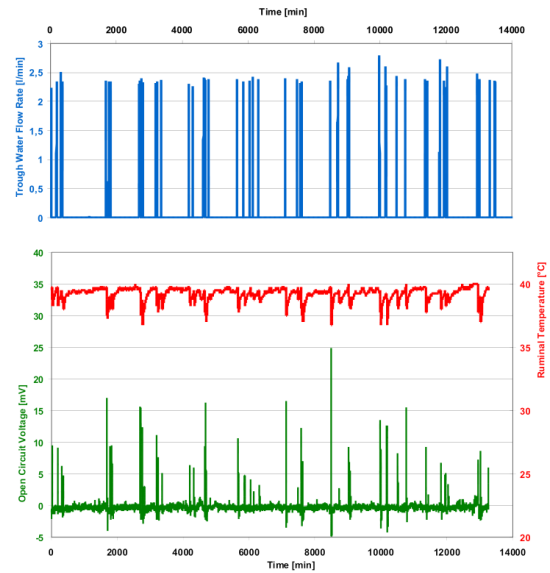
The reticulum with its better thermal conditions was inaccessible for this experiment. The bolus was placed in the rumen of a cannulated cow for 221 hours. Bolus temperature and voltage of the thermoelectric generators were recorded with a Track-It<sup>®</sup> data logger (Monarch Instrument, Amherst, NH) at a sample rate of 30 seconds. The trough water temperature and flow rate during drinking were recorded using a mikromec<sup>®</sup> multisense (Technetics, Freiburg i. Br.) data logger.

The *in vivo* experiment was carried out according to German animal protection legislation (Reg. No. 14-004/11). The animal was a Holstein Frisian being dry and feeding on hay *ad libitum*.

### 3 Results

The trough water temperature was 10 °C. The water intake per day varied between 40 and 60 ℓ. Trough water flow rate, ruminal temperature profile, and generated thermoelectric voltage measured during the entire experiment are depicted in Figure 2. It is evident, that each water flow coincided both with a decrease of ruminal temperature and an increase of voltage.

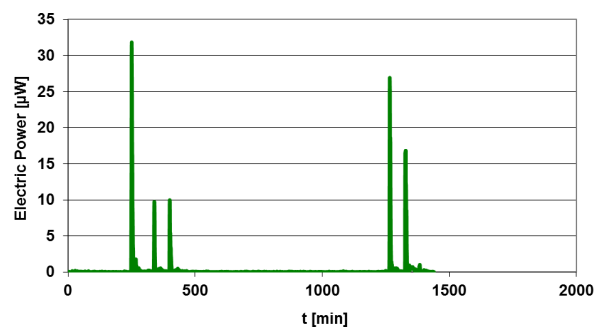
The average ruminal temperature during this *in vivo* study was 39.2 °C, as expected in healthy cattle. Temperature differences of up to 2.25 K were detected during the 13250 minutes (221 hours) of the experiment. The maximum open circuit voltage of 25 mV was recorded at minute 8488. Peak voltages occurred approximately five minutes after water intake.



**Figure 2:** Trough water flow rate, ruminal temperature, and generated open circuit voltage during the entire experiment.

Considering the generated voltage, the amount of water taken in appears to be of small importance. For instance at minute 8488 a voltage of 25 mV was generated by a water intake of *ca.* 16 ℓ, while an intake of 14 ℓ caused a voltage of 9 mV at minute 13006. This suggests that other parameters may be of greater importance, e. g. the position of the bolus within the reticulorumen.

Electrical power was generated periodically for approximately ten minutes after each drinking event. Thus the generated continuous power was low. For example the electric power generated on day 2 is shown in Figure 3. This day five power peaks occurred, the highest with 32 μW at 250 min. The day's average of generated power amounted to 0.31 μW.



**Figure 3:** Electric power generated in the reticulorumen at day 2 of the experiment.

Furthermore, the energy generated per day (Table 1) was calculated from the generated electric power. The energy generated per day averaged to 14.4 mJ. The generated energy peaked at day 2 with 26.7 mJ.

**Table 1:** Energy harvested in the reticulorumen per day.

Day	Harvested energy per day [mJ]
1	8.1
2	26.7
3	7.9
4	14.9
5	10.5
6	23.5
7	12.4
8	18.3
9	7.6

## 4 Conclusion

This study aimed at the development of a persistent energy harvesting power supply for a ruminal pH-monitoring system in cattle. The thermal gradients, which inevitably occur in the reticulorumen during water intake, were utilized to generate electric energy. However, some effort in optimising the performance yield is still needed to supply a micropower boost voltage converter sufficiently. More effective thermopiles should be used and the thermal capacity of the bolus increased. A drastic increase of generated power is expected from putting the bolus directly into the reticulum and exploiting its higher heat differential. Thus, the feasibility of thermal energy harvesting in the reticulorumen of cattle is proven, but also the necessity of further research.

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### Author's Statement

Conflict of interest: Authors state no conflict of interest. Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the

tenets of the Helsinki Declaration, and has been approved by the author's institutional review board or equivalent committee.

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