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# Vascular turbine powering a cardiac pacemaker: an in-vivo case study

Case report

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## Abstract

**Background:** Today's medical devices are powered by batteries with a limited energy storage capacity. Depleted batteries have to be replaced, exposing the patients to the risk of adverse events. Thus, a method for harvesting energy inside the body is desirable since it would allow building devices without batteries.

**Methods:** A miniaturized intravascular Tesla turbine was implanted as an arteriovenous shunt between the common carotid artery and external jugular vein of a pig. The harvested energy was used to power a custom-built temporary cardiac pacemaker.

**Results:** At a flow rate of ~150 ml/min, an output power of 0.4 mW was measured. Successful ventricular pacing was performed.

**Conclusion:** Harvesting energy from the circulation using an intravascular turbine is technically feasible and provides enough energy to power a cardiac pacemaker.

## Keywords

Cardiac pacing, energy harvesting, intravascular turbine

## 1. Introduction

Most of today's active medical devices are powered by primary batteries with limited energy storage capacity. Therefore, active devices such as cardiac pacemakers need to be replaced regularly which accounts for ~25% of all implantation procedures [1]. These repeated surgical interventions expose the patient to a higher risk of complications (e. g. infections, bleedings). In addition, surgical re-interventions increase healthcare costs. Intracorporeal energy harvesting may offer an elegant way out. Furthermore, energy harvesting is also motivated by the possibility to miniaturize devices since the battery size dictates their volume. Although several concepts for intracorporeal energy harvesting have been proposed, few have been implemented *in vivo* [2]. Harvesting energy from arterial blood flow may offer a reliable and continuous source of energy.

## 2. Case presentation

The purpose of the present study was to test if a miniaturized intravascular turbine could power a cardiac pacemaker to pace a pig's heart.

### 2.1. *Vascular turbine*

We manufactured a dedicated prototype of a Tesla turbine for *in vivo* testing (Figure 1, [3]). The custom-made turbine rotor consists of seven stainless steel discs (ø 10 mm) mounted on a shaft and attached to an electromagnetic generator (MG204, Kinetron, Netherlands). Blood flows between the tightly spaced discs from the outer diameter towards the shaft where it exits in axial direction. Hence, it drives the rotor by friction forces. The main casing of the turbine was made out

of polycarbonate, the in- and outlet were 3D-printed (Alaris 30 / VeroWhitePlus, Objet, Israel).

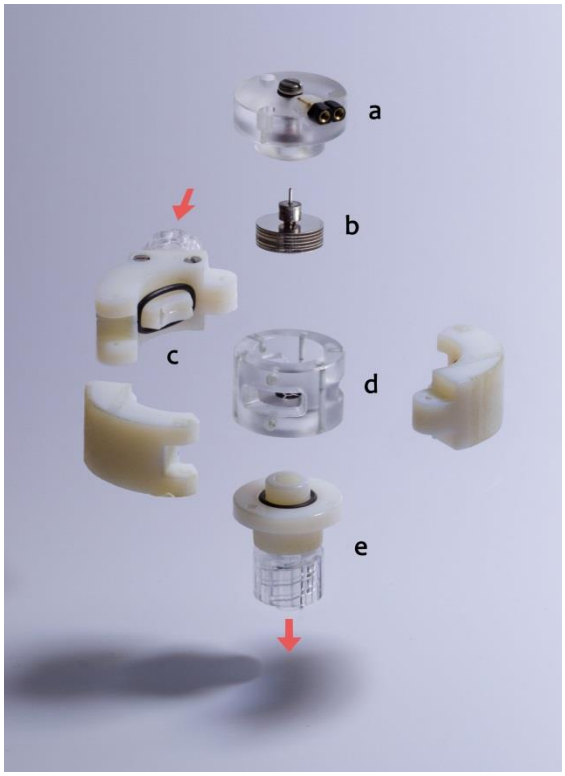


**Figure 1.** Intravascular turbine consisting of (a) cover including generator stator and output terminals, (b) rotor shaft with generator magnets and turbine discs, (c) inlet connector and turbine nozzle, (d) main casing and (e) outlet connector

### 2.2. *Experimental setup*

The acute animal study was performed on a 60 kg domestic pig. The animal was placed in the recumbent position under inhalation anesthesia. We performed a neck-dissection and inserted two 8.5 F high-flow sheaths (Arrow-Flex, Arrow, USA), one into the left common carotid artery and one into the left external jugular vein. Subsequently, we intravenously administered one bolus of 7500 IU heparine. The turbine was then implanted as an interponate between both sheaths to create an arteriovenous (AV) shunt. Blood flow through the shunt was continuously measured using an ultrasonic flow sensor. Pressure drop over the turbine was measured by two pressure transducers.
Ten minutes after administration of heparine, we measured an activated clotting time of 182 seconds and a platelet count of $399 \cdot 10^9$/l. We first measured the turbine's power output using an electrical resistor to simulate a consuming device. Subsequently, the vascular turbine generator was connected to a custom-built single-chamber pacemaker. A bipolar pacing wire (TME 66T, Osypka, Germany) was connected with this pacemaker and sutured onto the left ventricle after sternotomy. The trial was approved by the Ethical Committee of the Veterinary Department of the Canton of Bern, Switzerland, and performed in compliance with the Guide for the Care and Use of Laboratory Animals.

### 2.3. *Results*

An output power of up to 417±102 μW at a mean rotor speed of 1770±237 rpm was measured. Mean flow rate through the system was 150.3±12.2 ml/min, decreasing below 100 ml/min towards the end of the experiment when the turbine stopped spinning (after 16 minutes). Correspondingly, the pressure drop over the turbine increased from 37.8±5.4 mmHg to ~48 mmHg (Figure 2).
During the experiment, we successfully performed ventricular pacing (Figure 3).

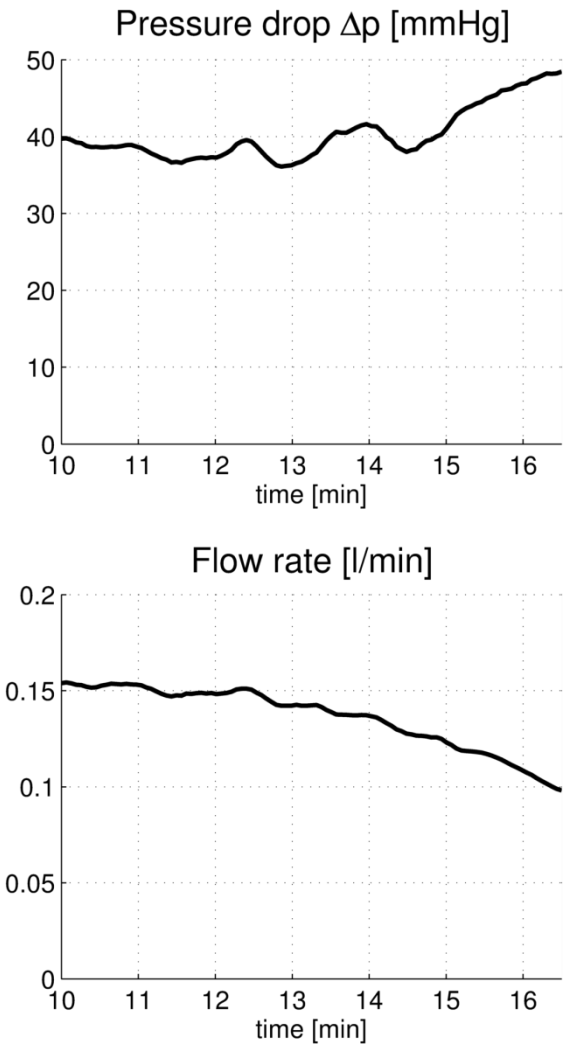


**Figure 2.** Pressure drop over the turbine (top) and flow rate through the shunt (bottom)

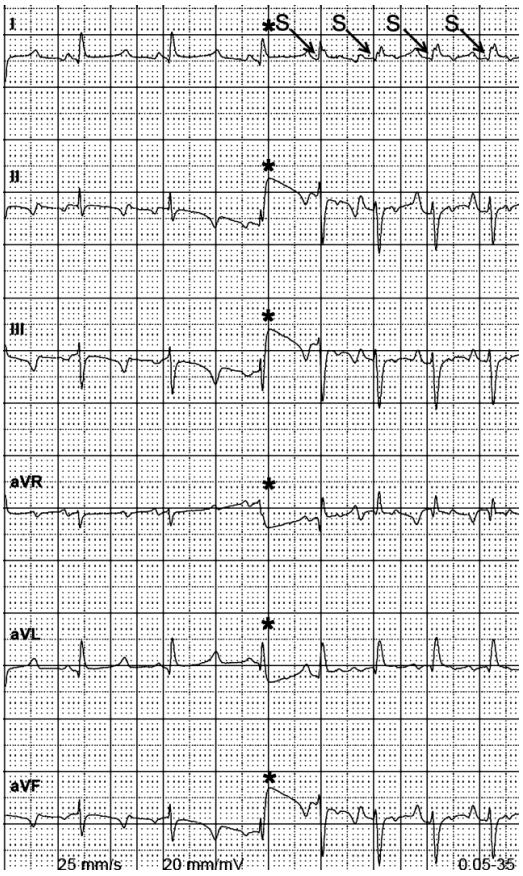


**Figure 3.** ECG recorded during pacing. The asterisk indicates when the pacemaker was started. Prompt ventricular pacing was established (S).

## 3. Discussion

For the first time, energy was harvested from the circulation by an intravascular turbine in an *in-vivo* setting. Using the gained energy, we successfully paced a pig's heart with a custom-built pacemaker. We harvested 0.4 mW with an energetic conversion efficiency estimated to 5% [3].

The turbine prototype is built out of materials exhibiting high thrombogenicity to facilitate prototype manufacturing. In addition, the blood was only slightly heparinized. Despite that, the turbine spun for more than a quarter of an hour. Towards the end of the experiment, flow rate decreased and pressure drop over the turbine rose indicating ongoing deposit and growth of thrombi in the turbine. This trend coincided with the observation that the rotor had ceased to spin after a certain time. In addition to the thrombogenicity of the materials employed in this study, it is known that flows with excessive shear stress can lead to platelet activation and subsequent thrombus formation in downstream regions, in particular at sites of low shear stress [4]. Indeed, after dismounting the device, clotting was observed at several sites on the turbine wheel (Figure 4). Thrombi were detected between the discs: locally at the outer radius of the rotor but mainly towards the inner radius (shaft) and by the spokes carrying the discs. These thrombi did impair the flow explaining the observed increase in flow resistance. Once the rotor stands still, the jet entering the rotor domain is not smoothly decelerated as intended but recirculates [3]. Such flows favor clot formation. Further optimization of the device is crucial in order to avoid thrombus formation in general. First, all surfaces in contact with blood should be coated using anti-thrombotic materials or agents. Second, non-contact bearing technologies may be required to avoid rubbing at mechanical contact points. Third, the geometry should be optimized further towards an even shear stress distribution by limiting the nozzle velocity and designing for continuously accelerated flows also in the rotating part of the turbine. Spokes and struts present in the outlet should be eliminated to avoid flow separation. Finally, such an energy harvester depends on the suitable combination of implantation site, turbine type, generator design and consuming device.

From a medical viewpoint, the implantation of the device in an AV-shunt between the carotid artery and the jugular vein is not desired. However, the current prototype delivered ~40 times more energy than is actually required by pacemakers (10 μW) [5]. Thus, further miniaturization of the device and implantation in a smaller vessel (e. g. the internal mammary artery) may still offer enough energy to power a pacemaker.

**Figure 4.** Observation of thrombi on the rotor

This first *in vivo* study demonstrates the concept of powering implantable medical devices by an intravascular turbine. Clinical acceptance of the risks associated with endovascular devices for energy harvesting depends on the safety and the efficiency, i.e. the long-term durability of such a device. An intra-arterial implantation using an axial turbine would have the advantage of simpler

implantation compared to the shunt configuration. Ultimately, percutaneous catheter based implantation in a small artery would offer a simple deployment as already established in daily clinical practice.

## 4. Acknowledgments

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