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Intraurethral Energy Harvesting from Urine Flow as an Approach to Power Urologic Implants

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Abstract— **Active urologic implants, such as bladder stimulators or artificial sphincters, are a widely-used approach for therapy of urinary incontinence. At present these devices are powered by primary batteries or conventional wireless power transferring techniques. As these methods are associated with several limitations, human body energy harvesting can be a promising alternative or complement for power supply. This paper introduces an approach to harvest energy from the urine flow inside the urethra with a mechatronic harvesting system based on a hubless flow turbine. Using a test bench approximating the flow conditions of the lower urinary tract, the feasibility of the harvesting principle is shown in-vitro.**

Clinical Relevance— **Intraurethral energy harvesting to power implants for therapy of urinary incontinence can contribute to extend implantation times and thus avoid invasive surgical procedures.**

I. INTRODUCTION

A. Urinary Incontinence

Urinary incontinence (UI), which refers to any involuntary loss of urine, is a highly prevalent condition significantly affecting the patients' quality of life and represents highly relevant socio-economic problem [1]. Patients are reported to be more likely to limit social contact [1, 2] and suffer from exhaustion, depression and anxiety [3]. The estimated prevalence of UI is reported to range from 25 % to 45 % in different studies, while it is more prevalent among women and the proportion of affected patients is rising with increasing age [4]. However, determination of the exact numbers of patients is difficult due to the tabooing nature of the topic. With the demographic change taking place in many industrialized countries and the increasing average age of the population, a rising incidence of urinary incontinence is expected. [5] To treat UI conditions, conservative methods, such as training of the pelvic floor muscles, can be used. In severe cases surgical implantation of an artificial urinary sphincter is considered, which, however, is associated with a high complication rate and requires a complex invasive procedure. [6, 7]

B. Powering of Active Implants

Active implantable medical devices (IMDs) play an increasingly important role, not only in UI treatment, but in therapy and acquisition of biomedical data in general. The powering of these devices using primary battery technologies is associated with several limitations, such as compromising the device's size as well as the frequent need for replacement or recharging. Further currently used powering approaches, including wire-based methods or inductive coupling, often have disadvantages regarding size, biocompatibility or achievable power transferring depths, as especially the energy supply of IMDs in deep tissue layers presents a challenge. [8, 9]

Due to the mentioned limitations associated with conventional powering methods, energy harvesting from the human body is a widely investigated trend, which not only addresses the stated disadvantages but also opens a completely new field of novel energy self-sufficient implants with new actuator and sensor principles.

C. Human Body Energy Harvesting

Energy harvesting refers to the process of converting available energy from the surrounding area into small amounts of electrical energy [9] with the aid of a suitable technical device. The human body can operate as an active or passive source of energy. While passive energy is harvested from the patient's or user's everyday actions, such as breathing or walking motions, active energy harvesting requires activities the person especially executes for harvesting. [10] Since for passive energy harvesting the user is not consciously aware of the energy conversion process, it has the least impact on the patient's living conditions and is therefore focused in the research presented in this paper.

Various approaches to harvest energy from the human body using different underlying physical principles have been proposed in literature. Investigations show the feasibility of different harvesting concepts, including the harvesting of mechanical energy from body movements using piezoelectric elements in various in- and on-body positions, the harvesting of thermal energy from temperature differences using the

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Seebeck Effect or the harvesting of biochemical energy based on electrochemical reactions processing glucose or oxygen [9–11]. Human body fluids in particular present a specific potential source of energy that has been investigated in research. Regarding the harvesting of mechanical energy using fluidic flows or pressures, blood flow is of special interest. Pfenninger et al. drove a turbine generator by the cardiac output blood flow in a peripheral artery [12]. Furthermore, approaches to harvest biochemical energy by implementing biofuel cells have been proposed using different body fluids, such as urine, saliva [13] or human perspiration [14]. However, only very limited amounts of energy were shown to be harvested and a counter electrode is required, which is limiting the possibility to integrate these harvesting modules in an enclosed implant.

II. FUNDAMENTAL URODYNAMICS

Urine flow presents a potential source of energy that is not well investigated to date despite its promising flow conditions. The human bladder cycle is characterized by a filling phase of the bladder and a subsequent micturition phase during which the urine is voided through the urethra. The according urodynamic norm values are subject to a wide variation depending on the individual patient. The average cystometric bladder volume of a healthy adult is 350 to 550 ml, and micturition has to be inhibited voluntarily at a filling volume of 350 to 450 ml. During the filling phase, the intravesical pressure in the bladder is slightly increasing by up to 15 cmH_2O. The bladder neck stays closed due to the contraction of the sphincter which makes the urethral closure pressure exceed the intravesical pressure. The micturition phase is initiated by a relaxation of the urethral and pelvic floor muscles which opens the bladder neck and decreases the urethral closure pressure. The bladder muscles contract, which increases the intravesical pressure to about 25 to 80 cmH_2O, and the bladder is voided at a maximum flow rate of 20 to 35 ml/s and an average voiding time of 40.75 s. [6, 15]

The micturition pressure in the urethra is composed by a hydrostatic pressure, resulting from the height of fall, and the pressure applied by the contraction of the bladder muscle. At an altitude difference of 10 cm and a completely filled average bladder, a pressure of 48.3 cmH_2O results. The mean volume flow is calculated to 12 cm^3/s from the average micturition volume and voiding time in women according to [6].

A healthy adult produces 1000 to 1500 ml urine over the course of 24 hours and has a micturition interval of 4 to 5 hours. At night this cycle is interrupted and no micturition is conducted for 8 to 10 hours. [15] The female urethra measures about 4 cm in length and has an average diameter of 8 mm, while the male urethra has a slightly smaller diameter of 7 mm. Since urethral tissue is very elastic it can be extensively stretched. [6]

III. METHODS

The aim of this study is the development and experimental validation of an energy harvesting system gaining mechanical energy from urine flow and converting it to electrical energy using a test set-up true to scale to prospectively enable the autonomous operation of active urologic implants.

A. *Harvesting Principle*

The targeted implantation of the energy harvesting system inside the urethra causes several requirements and limitations regarding the choice of the harvesting principle. Besides a high miniaturization potential a complete integration of the harvesting system and the downstream electrical modules is desired in order to avoid perforation of urethral tissue. Furthermore, the need for a high biocompatibility requires the hermetic sealing of modules containing critical substances. In the presented research a harvesting module consisting of an electric generator and a flow turbine was investigated as this harvesting principle meets the above-stated requirements. Regarding the turbine type an axial flow propeller turbine with fixed blades was chosen. This allows the reduction of the overall size as well as the decrease of the structural complexity of the turbine unit.

B. *Design of the Harvesting Module*

The concept of the turbine-based harvesting module is depicted in Fig. 1. Eight sintered neodymium cuboid magnets (NeFeB) are attached in circumferentially equally spaced notches on the turbine ring. Eight respective opposite iron core coils (Fastron Group, 1500 µH, 0.125 A) are excited simultaneously when the turbine is running and can then be connected in series, doubling the induced voltage. This results in a three-phase alternating current. The integrated rotating part is designed to be a staflo turbine as this principle with the generator unit being outside of the flow channel has several advantages regarding the targeted application. Using this turbine type, the stator can serve as a dry area and contain the electronic components of the implanted module in the useable housing space, which allows for a better miniaturization of the implant. Since only the turbine with fixed magnets is placed in the flow, the number of components being in contact with urine is reduced to a minimum.

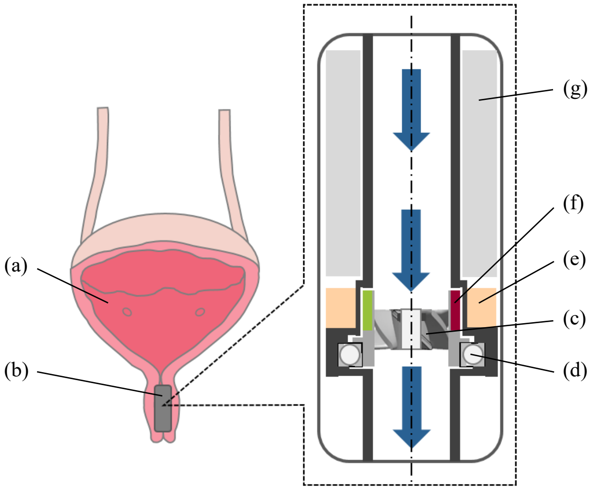

Figure 1. Schematic representation of the bladder (a) with the implant's location inside the urethra (b) and the design of the harvesting module (containing the turbine (c), bearing (d), coils (e), magnets with opposite poles (f) and usable space inside the housing (g)). The arrows indicate the direction of urine flow.

Furthermore, the concept of a hubless turbine allows for usable space in the turbine center which can be used to link medical equipment for the implantation and explantation process or to penetrate the entire implant in an emergency situation, for example with a catheter. The design avoids the use of a through-going shaft and the additionally required shaft suspensions, which greatly reduces the complexity and size of the generator unit. Thin-section bearings (6700 2RS/C) are chosen as they minimize the required installation space due to their small cross-section. For turbine design literature-based tools proposing specific turbine types and dimensions for certain pressures and flow rates were used. The specific speed n_q is a key figure in turbine design giving a statement about the rotational speed and serving for the further design of the used straflo turbine [16].

$$n_q \le \frac{850}{\sqrt{h \cdot 10^2}} \le \frac{850}{\sqrt{0.483\, m \cdot 10^2}} \le 122.31\, r/min. \qquad (1)$$

For propeller turbines in particular, a specific speed of 100 to 250 r/min can be expected [17]. Thus, the calculated value can be assumed to be plausible. Based on the specific speed approximated in (1), where the equation from [16] was adapted to the 100 times smaller scale of the demonstrator, the number of blades can be determined using the determination method modified for turbines with small dimensions by [18]. As the number of blades is recommended to be reduced with decreasing turbine size, a number of 5 blades is chosen in the presented study. The optimum angle of attack of the blades depends on a large number of factors and cannot be determined exactly analytically. The possibility of empirical testing of different angles of attack is pointed out while an angle of 45° is used in the presented study. The turbine has an outer diameter of 10 mm, with a maximum of 12 mm at the bearing support. The housing for the harvesting demonstrator and the turbines were additively manufactured (Fig. 2).

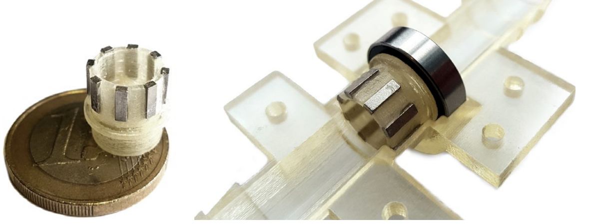

Figure 2. Additively manufactured turbine with attached magnets (left) and turbine with bearing inserted in one half housing (right).

C. *Test Set-up Resembling Human Micturition*

A simplified model-like representation of the urinary tract on a scale of 2:1 was set up for testing of the harvesting demonstrator (Fig. 3). The size of the test set-up was chosen due to the availability of components and simplified manufacturing and handling. A cylindrical glass container served as a liquid reservoir. A nylon tube with an inner diameter of 8 mm formed the connecting link between the reservoir and the harvesting module. Water was used as a test liquid running the harvesting module since it resembles urine in its density and flow characteristics.

By applying the model laws of Reynolds and Euler geometrical and physical similarity of the test set-up is given. Premising Reynolds and Euler number to be constant, analogies for pressure, friction and inertia forces between reality and the model can be derived. Since the dimensions of the demonstrator are twice the size of the original module, the pressure of 48 cmH_2O is divided by four to 12 cmH_2O in the model according to Euler's law. The flow velocity in the tube is mainly dependent on the height of fall which is set to 12 cm accordingly. The cross-sectional area of the pipe and the density of the used liquid is assumed to be constant.

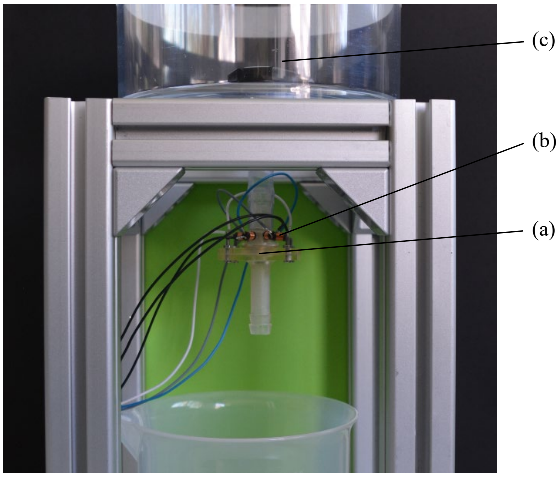

Figure 3. Test set-up to validate the harvesting module (a) with attached coils (b) and a glass container serving as a liquid reservoir (c).

D. *Functional Validation*

The main aspect of this research is the experimental validation of the electrical performance of the micro-generator. For this purpose, the test set-up was used to simulate stationary micturition procedures. In test runs the mean effective voltages and frequencies at the three phases were measured respectively. Test runs in open-circuit operation and power matching operation with load resistances of 11.8 Ω, which equals the internal resistance of one pair of coils, were conducted. The voltage frequency was then used to derive the rotational speed of the turbine, whereas four periods of the voltage curve correspond to one complete rotation of the turbine. Outlet water volume and voiding time were recorded in order to verify the resulting volume flow and outlet velocity.

IV. RESULTS

A uniform sinusoidal curve of the induced voltage is recorded for each phase respectively. Despite a noticeable cogging torque caused by the coils' iron cores, the turbine showed a high degree of revving power. A short run-out of the turbine in case of stall was observed. The rotational speed was in the range of 94 to 98 r/s in open-circuit operation while a maximum open-circuit voltage U_0 of 824 mV per phase was observed.

In power matching operation the mean effective voltage of the measured phases decreased to 363 mV with a mean deviation of 17.5 mV between phases. The rotational speed of the turbine in these runs was in the range of 86 to 94 r/s. Taking both the open-circuit voltage average value and an internal resistance of the coil pairs of 11.8 Ω into account, an effective power output P_{out_P} of 14.4 mW per phase can be calculated according to (2), which leads to a summarized effective total power output of 43.2 mW.

$$P_{out_P} = \frac{U_0^2}{4 \cdot R_i} = \frac{(824\ mV)^2}{4 \cdot 11.8\ \Omega} = 14.4\ mW. \tag{2}$$

The achieved efficiency can be calculated to 47.7 % from the ratio of the total generated power output to the theoretical maximum power from potential energy derived from the volume flow and height of fall. Assuming a constant efficiency level, 27 mW could be generated with the energy harvester in original size according to the used model laws.

V. DISCUSSION AND OUTLOOK

Urine flow presents a promising source of energy, though harvesting the available energy in order to use it to power applications remains a challenge. The general feasibility of a harvesting approach using a turbine-based micro generator was shown in the presented study. The developed harvesting system was proven to convert the mechanical energy of the fluid flow into electrical energy with a calculated efficiency rate of 47.7 %. Using ferrit core coils a maximum effective voltage of 824 mV was induced, which results in a maximum power output of 43.2 mW under load. Transferring the accomplished efficiency and power output to the full-scale harvesting module and parameters of the human micturition process, the achieved energy output is promising and presents a viable basis for future research. However, certain characteristics of the physiological micturition process have been approximated in the conducted experiments, mainly concerning the variable course of the volume flow during micturition and the biochemical properties of urine. Besides the further miniaturization and design optimization of the harvesting module, future steps therefore include the more accurately simulation of the micturition process in a test bench developed for this purpose [19] as well as the use of artificial urine as a test liquid resembling the formation of urine stone, which could possibly affect the micromechanics of the generator. For geometrical design studies simulations as well as empirical studies are conceivable.

The energy harvester is developed to serve as the central source for the self-sufficient energy supply of mechatronic implants. The aim here is to optimize the efficiency to such an extent that sufficient energy is available even under suboptimal conditions. This includes, for example, short micturition durations or weak bladder pressures, which greatly reduce the energy yield and the flow velocity of the urine. However, if the efficiencies achieved with a turbine are directly transferred to the planned original dimensions of the implant and the general conditions in the human body, the achievable energy output is promising and provides a valid basis for continuing the research work on the developed concept. Self-sufficient miniaturized sphincter implants could save the growing number of incontinence patients from invasive surgeries requiring multiple incisions and simplify the daily handling of their implant.

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