Energy Harvesting for In-Ear Devices Using Ear Canal Dynamic Motion

Aidin Delnavaz and Jérémie Voix

***Abstract*—In this paper, we study the possibility of using energy harvesting from ear canal dynamic motion as a source of power to replace the use of batteries for in-ear devices. Two hand-made micropower generators capable of scavenging energy from ear canal deformation are presented in this paper: 1) a hydroelectromagnetic energy harvester and 2) a flexible piezoelectric generator. The experimental results show that 3.3 mJ of energy per mouth opening and closing cycle is available from ear canal dynamic motion. If we consider that possibly thousands of such cycles occur daily, ear canal dynamic motion could prove to be a likely source of energy for in-ear applications.**

***Index Terms*—Ear canal dynamic motion, electromagnetic energy harvester, piezoelectric energy harvester.**

I. Introduction

THE most limiting aspect in mobile technology is the electrical power supply. It restricts autonomy and has a direct impact on the weight and size of electronic devices. Although the use of batteries is still widespread, their cost and impact on the environment is an increasing problem.

According to the World Health Organization [1], hundreds of millions of people suffer from various types of hearing impairment, and tens of millions of hearing aids are currently in use. Hearing aids and other types of in-ear devices, such as digital earplugs, smart hearing protectors, and Bluetooth communication earpieces, typically have low power consumption and strict size limitations. In recent years, they have been substantially modified and are becoming less energy consuming. Since energy harvesting technologies are usually suitable for low-power portable devices, they are gaining interest as an alternative to batteries for in-ear devices.

In general, batteries and energy harvesting from the environment or the human body are the only possible ways to power in-ear devices. In this paper, we investigate a new source of energy harvesting for in-ear devices that would come from the wearer: ear canal dynamic motion. This paper is organized as follows: Section II provides an overview of recent advances in various known energy source technologies for in-ear applications. Ear canal dynamic motion as an unexploited source of energy is studied in Section III. A hydroelectromagnetic power generator and a piezoelectric ring energy harvester were designed, modeled, built, and finally tested. Their results are presented in Sections IV and V and are discussed in Section VI. Finally, conclusions are drawn in Section VII.

Manuscript received July 16, 2012; revised October 10, 2012 and December 6, 2012; accepted January 9, 2013. Date of publication January 25, 2013; date of current version July 18, 2013. This work was supported by Sonomax Technologies Inc. and its "Industrial Research Chair in In-Ear Technologies."

The authors are with the Department of Mechanical Engineering, École de Technologie Supérieure, Montreal, QC H3C 1K3, Canada (e-mail: jeremie.voix@etsmtl.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIE.2013.2242656

II. Overview of Energy Sources

A. Battery Technology

A battery is composed of one or more electrochemical cells that convert stored chemical energy into electrical energy. Batteries are classified into two main categories: disposable and rechargeable.

Disposable batteries: During the past decades, mercury and silver were common ingredients in hearing-aid batteries. The use of mercury in hearing-aid batteries was later banned and discontinued because mercury is highly toxic for the environment. Silver is rarely used nowadays because it is costly and does not effectively prolong battery life. Today, nearly all hearing-aid batteries are zinc–air batteries, that is, using a reaction between zinc as the major ingredient and ambient air. The zinc–air battery lasts more than twice as long as comparably sized mercury or silver batteries, but its life span is still limited, and the continuous need for replacement represents a high cost of operation and a serious impact on the environment.

Rechargeable batteries: It is possible to recharge hearing-aid batteries by using nickel–metal hybrid or lithium-ion rechargeable batteries and a battery charger [2]. Rechargeable batteries currently have a very limited power capacity and must therefore be recharged every night. This need for frequent recharging remains inconvenient or even difficult for individuals with limited dexterity or vision. This problem can be overcome by using a wireless battery charging system: The hearing aid may simply be placed within the charger to charge the battery by means of an inductor circuit [3]. While these types of hearing-aid rechargers are an improvement, the battery power capacity is still limited, and users must rely on a single piece of hardware, i.e., the wireless charger, which is cumbersome and inconvenient. In short, rechargeable batteries are currently costly and have an average maximum life span of less than a year.

Other solutions: Microfuel cells [4], nuclear cells [5], and microturbine generators [6] would seem able to power mobile devices; however, reliance on chemicals to generate energy is unpopular with users, for example, having to refuel when supplies run out.

B. Energy Harvesting From the Environment

Energy can be harvested from environmental sources such as sunlight, sound, and ambient radiations.

Sunlight: Among the possible environmental energy sources, solar power has been already attempted for hearing aids. Solar-powered hearing aids either have a battery recharging system that uses a photovoltaic panel [7] or are designed to have a photosensitive surface on the hearing-aid shell [8]. The first type of solar-powered hearing aid meets the autonomy restriction criteria, whereas the second type is more externally exposed in order for the photocell to produce electrical current when exposed to ambient light. For example, a 70-mm^2 amorphous silicon cell must be mounted on the visible faceplate of a hearing aid in order to generate 200 μA in 0.9 V at one tenth of full sunlight [8]. In practice, however, hearing-aid users frequently request that the device be completely in the ear canal, that is, not visible from the outside: This reduces sunlight exposure to the point of discouraging the use of solar power for in-ear devices.

Sound: Sound is a regular mechanical vibration that travels through matter as a waveform. Its energy can be harvested by a sound-driven nanowire-based generator [9]. When a sound wave strikes the generator, ZnO nanowires start vibrating, and this generates piezoelectric potential on electrodes. This technology is still in its preliminary stages, and the amount of power it produces is still very low (0.3 μW) for a device of 1 cm^2 [9].

Ambient radiation: The energy of ambient radiation sources, such as near infrared [10], X-rays [11], and radio frequency [12], can be also captured and converted into electricity. Here, again, the fundamental dependence upon the amount of energy available in the area of application, as well as the limited size of in-ear devices, eliminates the possibility of any such applications.

C. Energy Harvesting From Human Power

The human body is an abundant source of energy. Human motion and body heat can be harvested and used to power portable devices. Many attempts have been made in the past to tap this source.

Swinging arm: One of the first and well-established human-powered mechanisms is the auto-winding system built for mechanical or automatic watches. It consists in harvesting energy from the swinging motion of the arm [13].

Walking: Walking is another type of physical activity that has even more associated energy. For instance, a considerable amount of power is available from heel strikes during brisk walking. Piezoelectric materials and rotary magnetic generators have been already employed in shoes in order to harvest energy as a person is walking [14], [15]. This energy can be also harvested by mounting a mechanism at the knee and converting the kinematic motion of the knee through a generator [16]. This knee-mounted energy harvester is claimed to produce an average of 5 W of electricity, which is about ten times that of shoe-mounted devices.

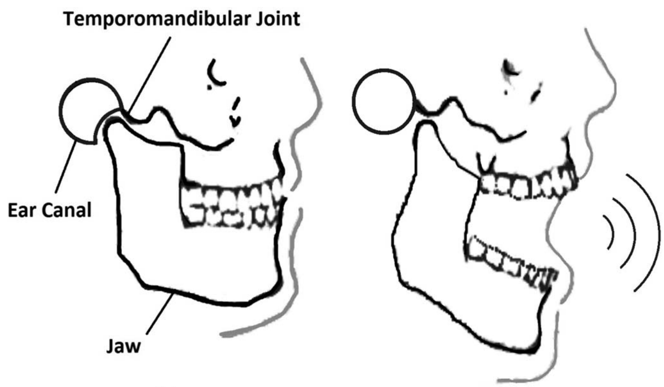
Power generated during human walking is not limited to shoe- or knee-mounted generators. A suspended-load backpack generates electricity from the vertical movement of carried loads during normal walking and can generate up to 7.4 W [17]. In addition, a small spring magnet in a coil, oscillating from human body motion, is able to supply 2.5 mW of power [18]. Use of the aforementioned human-powered generators is not suited for in-ear devices because, in most cases, the energy harvesting site is far from the ear, and thus, wiring would probably be uncomfortable for the user.

Body heat: Heat is a source of energy that can be found throughout the human body. Heat can be harvested as energy as a result of the temperature difference between two sources (thermoelectricity) or the temperature fluctuation in one area (pyroelectricity). Since human body temperature is mostly constant, the temperature gradient between the ambient and the human body can be converted into electricity by using an appropriate thermoelectric generator (TEG) [19]. For example, a TEG that extracts energy from human tissue warmth has been already developed to power hearing aids [20]. This thermoelectric module can be attached to the skin very close to the ear, but the power harvested is as little as several nanowatts for a 10 °C temperature difference. To obtain more thermoelectric power, a larger number of arrays would be needed and, in turn, larger areas of skin. Moreover, the Carnot efficiency is fundamentally limiting for the thermal efficiency of TEGs, and it is highly influenced by ambient temperatures and radically drops in a warmer environment.

From what has been presented hereto of the advances in portable device technologies and power source technologies, it can be concluded that batteries have evolved more slowly due to technical and technological issues [21]. Similarly, sources of energy from the environment or the human body used so far are either insufficient or too limited for in-ear devices, and energy harvesting techniques involving these power sources are not yet suitable for hearing devices. Consequently, an appropriate power source still needs to be found.

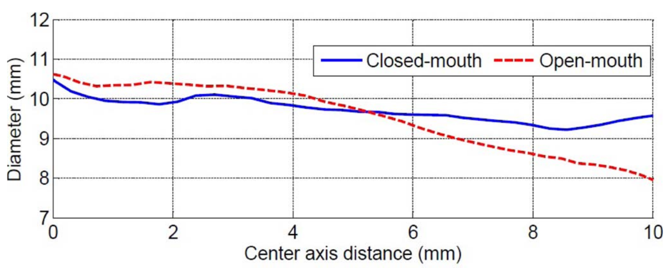
III. Ear Canal Dynamic Motion: An Unexploited Source of Energy

There is a source of kinetic energy in the human body that is quite unnoticeable and has never been considered as a source of energy but shows great promise for in-ear applications [22]. The ear canal is a dynamic environment, and when chewing, smiling, yawning, eating, or speaking, the ear canal wall moves, expanding and compressing. One can more easily perceive this movement by placing the tip of the auricular finger at the opening of the ear canal while opening and closing one's mouth. Ear canal deformation caused by temporomandibular joint (TMJ) activity is also known as *ear canal dynamic motion*. The TMJ, which is also referred to as the jaw joint, is located near the ear canal, and its slight movement when the mouth opens and closes affects the ear canal shape and changes its geometry, as shown in Fig. 1.

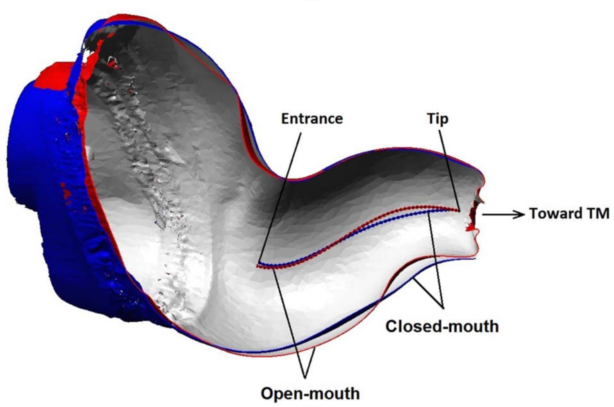


(a) (b)

Fig. 1. Schematic representation of the ear canal dynamic motion. (a) Closed-mouth position. (b) Open-mouth position.



(a)



(b)

Fig. 2. Earplug geometries in *open-mouth* and *closed-mouth* positions. (a) Ear canal geometry. (b) Earplugs overlay.

The diameter of a typical ear canal along the center axis for the *open-mouth* and *closed-mouth* positions of the jaw is represented in Fig. 2. This figure also clearly shows that the jaw movement can change the ear canal diameter or volume. This change may be positive, negative, or mixed and does not necessarily follow a similar trend for all individuals. For example, the ear canal shown in Fig. 2 is mostly expanded at the entrance section and compressed at the tip section upon opening the mouth. The range of ear canal diameter changes due to jaw joint movement significantly varies among individuals, but despite these variations, in most cases, these diameter changes seem quite conclusive for energy harvesting purposes.

Because of the low rate and the irregular nature of ear canal dynamic motion, a suitable generator structure is needed to enable energy harvesting in nonresonance conditions. Piezoelectric and electromagnetic transduction methods are the two most promising approaches for kinetic energy harvesting [23]. Thus, two energy harvesting mechanisms, including a hydroelectromagnetic generator and a piezoelectric ring mechanism, are proposed in this paper for the expansion motion occurring at the entrance part of the ear canal and will be presented in the following sections.

IV. Hydroelectromagnetic Energy Harvester

A hydroelectromagnetic system is developed here to harvest energy from jaw joint activities. It is composed of a magnet in a tube of water that is surrounded by a 1000-turn coil made of a 40-μm copper wire. One end of the tube is attached to an expandable earplug. By injecting water into the system using a water filling syringe, the earplug expands to snugly fit against the ear canal walls. Furthermore, water rises in the tube and sinks the magnet. By placing a fixed magnet in such a way that the same poles face each other, a repulsive force is produced keeping the free magnet suspended inside the tube, as shown in Fig. 3. As ear canal volume changes, the water level in the tube rises and falls. Consequently, the suspended magnet moves and induces voltage in the coil.

A. Available Power From the Ear Canal Dynamic Motion

The hand-made experimental setup is also equipped with a pressure gauge system to measure the variation of the water level in the tube by using the following equation:

$$P(t) = \rho g h(t) \tag{1}$$

in which $P(t)$ is the measured pressure in pascal, ρ is the density of water, g is the gravitational acceleration, and $h(t)$ is the height of water in the tube at time t. The force applied to the water column by the ear canal dynamic motion, i.e., $F(t)$, is obtained by

$$F(t) = P(t)A \tag{2}$$

where A is the cross-section area of the tube. Multiplying this force by the speed in which it is applied gives the instantaneous power, i.e.,

$$W(t) = F(t)v \tag{3}$$

where v is the absolute rate of changes in the water column and is defined as

$$v = \left|\frac{dh(t)}{dt}\right|. \tag{4}$$

Substituting (1), (2), and (4) into (3) yields the instantaneous available power, i.e., W_{av}, from the ear canal dynamic motion as follows:

$$W_{\text{av}} = \frac{AP}{\rho g}\left|\frac{dP}{dt}\right|. \tag{5}$$

To avoid high-frequency noise magnification during differentiation in (5), the total pressure signal passes through a Chebyshev low-pass filter. The filtered total pressure and the available power are presented in Fig. 4 for three cycles of opening and closing the mouth with the frequency of 1.5 Hz.

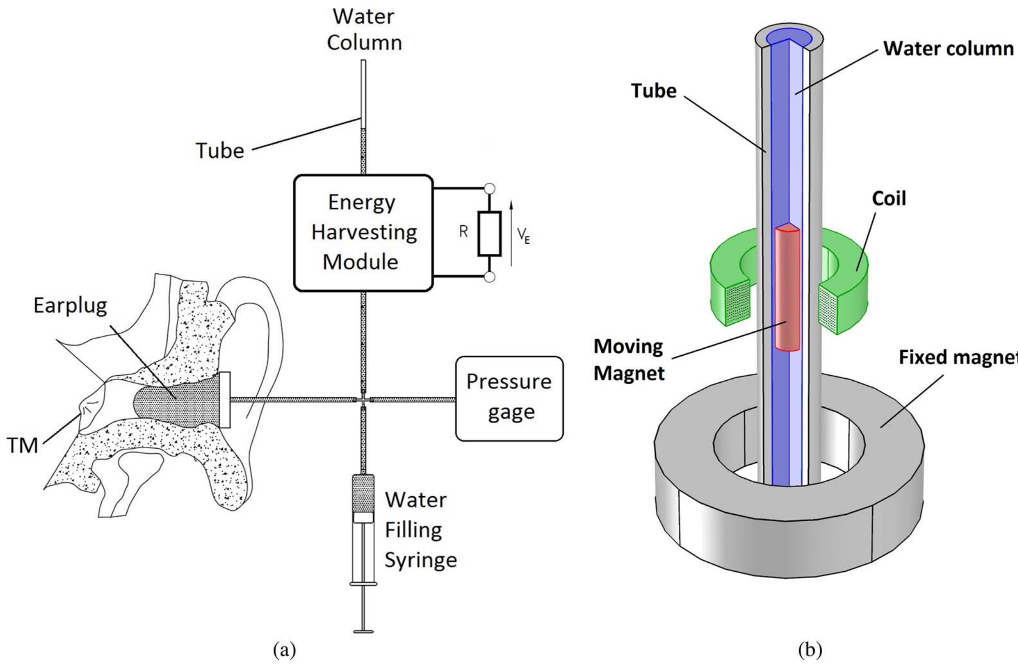


Fig. 3. Hydroelectromagnetic energy harvester. (a) Test setup. (b) Energy harvesting module.

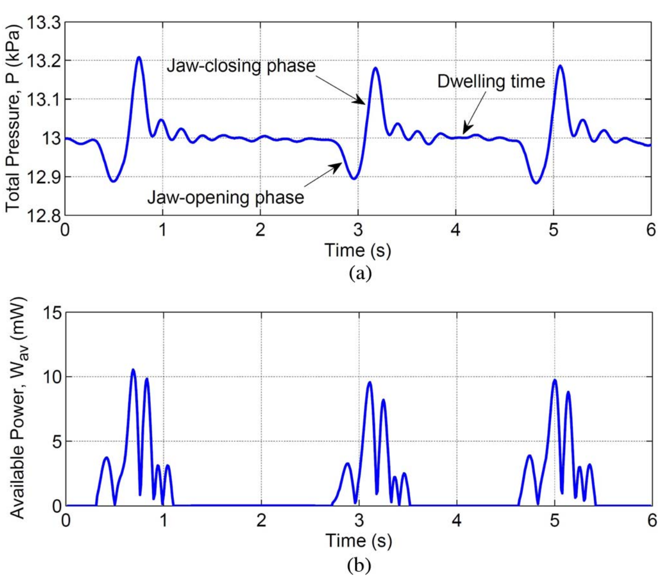


Fig. 4. Ear canal dynamic evaluation results. (a) Total pressure in the main column after applying a low-pass filter. (b) Available power during opening and closing of the mouth.

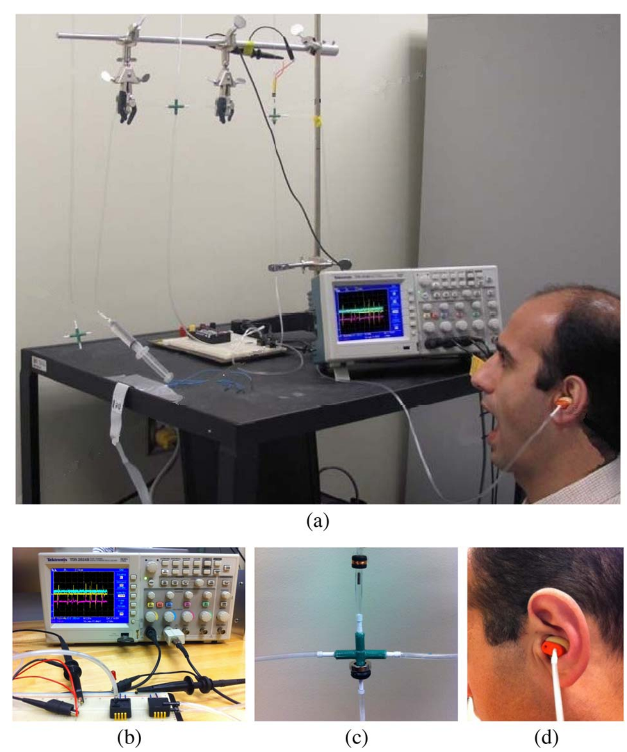


Fig. 5. Experimental setup for the hydroelectromagnetic energy harvesting system. (a) Overall view. (b) Pressure gauges and load resistance. (c) Energy harvesting module. (d) Expandable earplug in the ear canal.

Each cycle consists of two phases: 1) jaw-opening and 2) jaw-closing phases, as depicted in Fig. 4(a). In addition, there are dwelling times between cycles in which the mouth is stationary. Fig. 4(b) shows that the maximum available power is about 10 mW and is obtained in the jaw-closing phase while the pressure increases. By integrating the available power in this figure over one mouth opening and closing cycle, the average available energy is estimated to be 3.3 mJ, which is equivalent to an average power of 5 mW (3.3 mJ $\times$ 1.5 Hz). Furthermore, by multiplying this energy by the approximate number of 2200 chewing cycles per day [24], one obtains 7.3 J of chewing energy per day from ear canal dynamic motion. This amount of energy is equal to the energy consumption of a 1-mW hearing aid [25] during 2 h. Considering other forms of jaw activities such as speaking can increase this value considerably.

B. Experimental Measurements on the Hydroelectromagnetic System

The prototype generator and test setup is shown in Fig. 5. The geometrical parameters of the system are also listed in Table I.

TABLE I
HYDROELECTROMAGNETIC ENERGY HARVESTER PARAMETERS

Parameters	Unit	Value
Tube diameter	mm	2
Moving magnet diameter	mm	1.6
Moving magnet height	mm	6.4
Fixed magnet height	mm	3.2
Coil mean diameter	mm	6
Coil height	mm	2
Wire thickness	μm	40
Number of turns		1000
Coil ohmic resistance	Ω	214

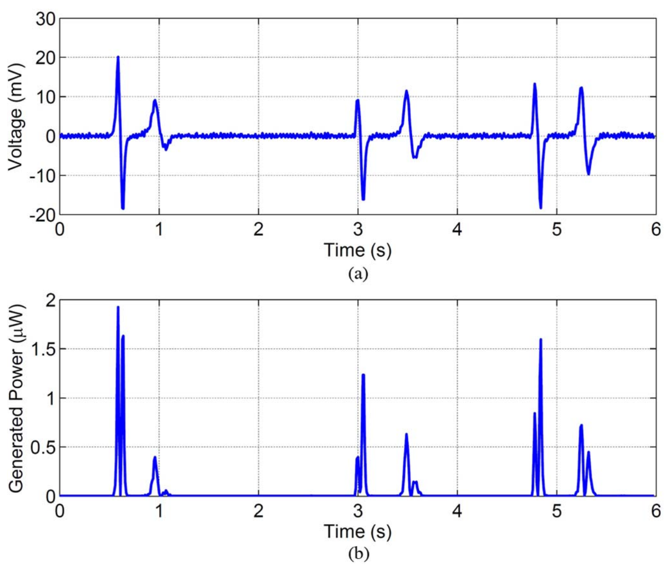


Fig. 6. Experimental results for the hydroelectromagnetic energy harvesting system. (a) Load voltage. (b) Generated power.

To perform this test, the moving magnet was inserted into the tube, and a similar polarity ring magnet was attached to the tube's exterior. The system was filled with water using a syringe until a pressure of 13 kPa was achieved. After evacuating all air bubbles, jaw joint movements were applied, and the voltage of the load resistor was measured. The load resistance was set equal to the coil resistance in order to ensure maximum power transfer. The voltage of the load resistor (V_E) as a result of the mouth opening and closing is shown in Fig. 6(a).

The power transferred to the load resistor is shown in Fig. 6(b) and is calculated as follows:

$$W_E = \frac{V_E^2}{R} \tag{6}$$

in which R is the load resistance, which is also equal to the resistance of the coil. In this figure, the maximum generated power is about 2 μW. By averaging in a cycle of mouth opening and closing, the average generated power would be 0.3 μW.

V. Piezoelectric Energy Harvester

The piezoelectric power generator includes a ring made of a piezo film sheet. The piezo film is a flexible sheet of polyvinylidene fluoride (PVDF) that is metalized with a silver ink coating [26]. Unlike other popular piezoelectric materials, such as PZT, PVDF is biocompatible and safe for energy harvesting from biological systems [27]. The ring is fabricated by cutting a piece of the piezo film sheet in a T-shape. The tips of the "T" cross are joined to make the shape of a ring, and its stem forms a tail that is connected to wires. This piezoelectric ring is mounted on a headset and is placed inside the ear canal, as shown in Fig. 7. The headset keeps the ring in position and prevents it from being ejected from the ear canal during jaw joint movement. By opening and closing the mouth, the piezoelectric ring is deformed and generates an electrical charge. A prototype piezoelectric ring was fabricated by hand to fit the ear canal presented in Fig. 2(a), and its geometrical parameters are listed in Table II.

A. Generated Power Measurement

The generated power depends on the output voltage of the piezoelectric ring. However, this voltage cannot be directly measured by an oscilloscope probe, because the capacitance of the piezoelectric ring and the resistance of the probe constitute a potential divider that makes the oscilloscope measure only a portion of the generated voltage. This portion varies depending on the frequency, and the corresponding 3-dB cutoff frequency is obtained by

$$f_c = \frac{1}{2\pi R_L C_p} \tag{7}$$

where $R_L = 10$ MΩ is the resistance of a typical "10×" oscilloscope probe, and C_p is the capacitance of the piezoelectric ring. C_p can be calculated for the ring with the size given in Table II by

$$C_p = \frac{\varepsilon \pi d h}{t} = 1.8 \times 10^{-10} F \tag{8}$$

in which d, h, and t are the diameter, height, and thickness of the piezoelectric ring, respectively, and ε is the permittivity. Consequently, the cutoff frequency from (7) is estimated to be $f_c = 6.6$ Hz, and below this frequency, the reading error is considerable. Obviously, the jaw joint does not normally move so fast, and hence, the measurement of the oscilloscope is not reliable.

As an alternative method, the average output power can be indirectly calculated. In this method, the charge produced by the piezoelectric ring is stored in a capacitor with known capacitance. Then, by measuring the voltage of the capacitor, it would be possible to estimate how much power has been generated. The proposed measuring setup is shown in Fig. 7.

In this figure, a voltage source in series with capacitance C_p represents the piezoelectric ring. The charge generated from ear canal dynamic motion is stored in a load capacitor C_L using a full-wave rectifier circuit depicted in Fig. 7. During the jaw-opening phase, two forward-biased diodes (D1 and D3) let the generated current flow. During the jaw-closing phase, the direction of current is reversed, and C_L is charged through reversed-biased diodes (D2 and D4). By using this configuration, the voltage across C_L increases twice for each cycle.

The generated charge in each phase is divided between the piezoelectric ring as a capacitor and the load capacitor

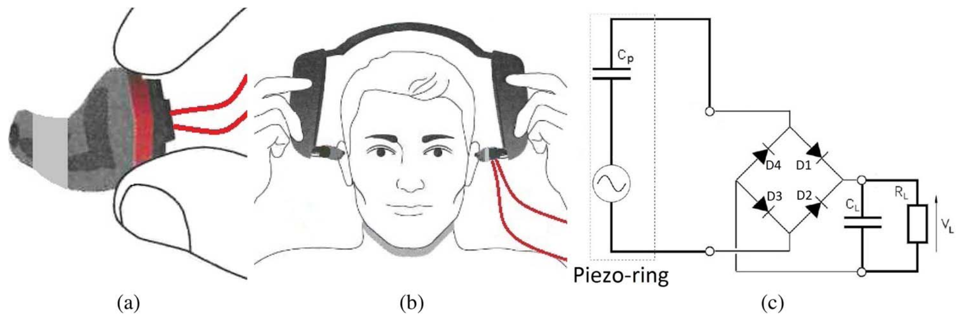


Fig. 7. Experimental setup for the piezoelectric energy harvesting system. (a) Earplug and piezoelectric ring. (b) Headset. (c) Capacitor charging circuit.

TABLE II
PIEZOELECTRIC ENERGY HARVESTER PARAMETERS

Parameters	Unit	Value
Ring diameter	mm	10
Ring height	mm	7
Piezo film thickness	µm	110
Permittivity	$\mathrm{F\,m^{-1}}$	107×10^{-12}

considering their capacitance values. Jaw joint movement usually has a constant periodic cycle; hence, the generated charge at each phase is always the same and has a value of Q. Then, at each new phase, Q is redistributed between C_p and C_L. Assuming $C_L > C_p$ and considering ideal diodes (zero voltage drop when forward-bias and no current under reverse-bias) and no current leakage, at the nth phase, the charge distribution is

$$Q + Q_p(n-1) + Q_L(n-1) = Q_p(n) + Q_L(n) \quad (9)$$

where Q_p and Q_L are the electric charge in C_p and C_L, respectively, and given by

$$Q_p(n) = V(n)C_p \quad (10a)$$

$$Q_L(n) = V(n)C_L \quad (10b)$$

$$Q_p(n-1) = -V(n-1)C_p \quad (10c)$$

$$Q_L(n-1) = V(n-1)C_L. \quad (10d)$$

The minus sign in the expression of $Q_p(n-1)$ accounts for the changing direction of the generated current at each new jaw phase. In fact, the charge stored in C_p at the jaw-opening phase has an opposite sign with respect to the generated charge at the preceding jaw-closing phase, and vice versa. Substituting (10) in (9) yields

$$V(n) = \frac{Q}{C_L + C_p} + V(n-1)\frac{C_L - C_p}{C_L + C_p}. \quad (11)$$

Assuming $V(0) = 0$, it is concluded that

$$V(n) = \frac{Q}{2C_p}\left[1 - \left(\frac{C_L - C_p}{C_L + C_p}\right)^n\right]. \quad (12)$$

Considering charge leakage Q_{leak} at each phase and voltage drop V_D across the diodes in forward-bias gives

$$V(n) = \frac{Q - Q_{\text{leak}} - 4V_D C_p}{2C_p}\left[1 - \left(\frac{C_L - C_p}{C_L + C_p}\right)^n\right]. \quad (13)$$

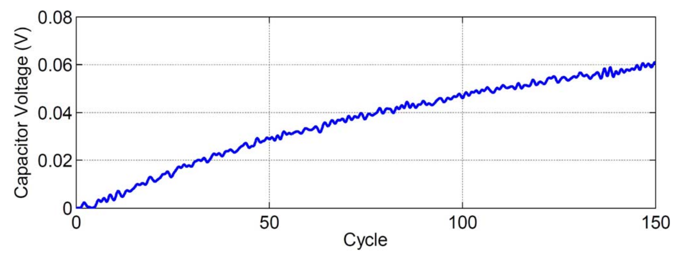


Fig. 8. Charging of a 24-μF capacitor by the piezoelectric ring energy harvester during 150 cycles of opening and closing of the mouth.

By measuring the voltage of the capacitor in phase n and knowing the other parameters, (13) can be solved for Q. Finally, the generated power can be calculated by

$$W_P = \frac{1}{2}\frac{Q^2}{C_p}f \quad (14)$$

in which f is the frequency of producing charges, which is twice the frequency of the jaw opening and closing cycle.

B. Experimental Measurements on the Piezoelectric Ring System

The circuit shown in Fig. 7 was used with Schottky diodes and a ceramic capacitor. The load capacitor had the capacitance of $C_L = 24$ μF with a measured leakage resistance higher than 10 GΩ. The measured forward voltage drop of Schottky diodes was $V_D = 0.4$ V, and their inverse leakage currents were measured to be less than 0.1 nA at 4.5 V. Consecutive jaw opening and closing cycles were applied to the system for a hundred seconds, and the results are represented in Fig. 8. This figure shows that the voltage of the load capacitor exponentially rises and reaches around 0.06 V after 150 full cycles. The frequency of jaw joint movement was $150/100 = 1.5$ Hz, which is equal to the frequency of jaw activities in the hydroelectromagnetic test.

The mean charge produced in each phase is estimated to be $Q = 5$ nC. Using (14), the generated power is approximately $W_p = 0.2$ μW.

VI. DISCUSSION

The experimental results of the hydroelectromagnetic and piezoelectric ring energy harvesting mechanisms prove the feasibility of using ear canal dynamic motion as a source of

TABLE III
HUMAN POWER SOURCES

Power source	Available Power (W)	Generated Power (W)	Reference
Walking	67	5	[16]
Arm motion	60	0.33	[28]
Blood pressure	0.93	—	—
Body heat from the head	0.6-0.96	1µ	[20]
Breath	1	3µ	[29]
Ear canal dynamic motion	0.005		
- Hydro-electromagnetic		0.3µ	This
- Piezo-ring		0.2µ	work

human power. Table III shows power recovery expectation from different human body sources of power, as discussed in [28], as well as the output power of one representative energy harvesting mechanism in each category. This table also includes the results of the proposed ear canal dynamic motion and the two respective energy harvesters.

According to Table III, the maximum achieved power is 5 W from the 67 W of power available from walking. This value amounts to 0.3 and 0.2 μW for the hydroelectromagnetic and piezoelectric ring mechanism, respectively, whereas 5 mW is potentially available from ear canal dynamic motion. These values indicate that the efficiency of scavenged power from ear canal activities is currently very low in comparison with arm and leg power generators. One reason for the poor performance of the proposed systems is that they have not been optimized in terms of design or dimensions. For example, the magnet configuration in the hydroelectromagnetic prototype is not optimum nor is the piezoelectric ring, which occupies only 2% of the volume in the active part of the ear canal. The main reason for this has more to do with the fundamental properties of ear canal dynamic motion. Simply put, the ear canal is not as dynamic as other parts of the body such as the foot or hand; its frequency is very low, and its displacement is in the submillimeter range.

Up to this point, the concept of using ear canal dynamic motion as a new source of energy harvested from human body power has been clearly validated by the proposed systems; however, this concept would need to be improved in the following areas before any practical usage could be made in the future.

(a) The cost of harvesting (COH) is an important factor to design future power scavengers. According to definition, COH is defined as [16]

$$\text{COH} = \frac{\Delta\text{metabolic power}}{\Delta\text{electrical power}} \tag{15}$$

where Δ refers to the difference between jaw activities with and without energy harvesting. The mechanisms discussed in the previous sections used to harvest energy were quite comfortable for the wearer, because the scavenged power was much lower than the available power. Similarly, any desirable energy harvester must have low COH, that is, the consumed metabolic power of the device must be restricted. Otherwise, it could lead to discomfort or even pain.

(b) The output of an energy harvester is not directly suited as power supply for circuits because of variations in its power and voltage over time. Therefore, a power management circuit is required to handle very low and variable feeding power by using advanced converting techniques, such as a direct ac–dc boost converter [30] or an adaptive dc–dc converter (between rectifier bridge and battery) [31]. Moreover, it must be capable of adapting its input to the energy harvester and its output to the load. It should also be self-starting to save energy while there is no jaw movement or when the harvester is idle [32].

(c) An appropriate battery or storage device is also required to receive intermittent power from ear canal dynamic motion and provide continuous power necessary to the electronic circuits of the in-ear devices. Such a system can be also used as a hybrid device in which an energy harvesting module gives the wearer more time between battery changes or charges and, hence, improves the autonomy and ease of use of in-ear devices.

(d) The current size of the system has to be further reduced for all the parts to fit inside the in-ear devices without affecting the performance of the system. Miniaturization processes can be effectively done by making a closed-loop water circuit inside the earplug for the hydro-electromagnetic system or using microelectromechanical system techniques to deposit piezoelectric layers on the surface of the earplug.

VII. CONCLUSION

Two energy harvesting mechanisms capable of using ear canal dynamic motion have been presented in this paper. The variation of ear canal volume was transformed into a variation of water level within a vertical tube in order to measure the total available mechanical power. This available power was then estimated to be 5 mW on average, which corresponds to 3.3 mJ of energy per mouth opening and closing cycle. This amount of energy can reach a few tens of joules per day depending on how many thousands of cycles occur during the day. The first system tested harvests some of this power through a hand-made hydroelectromagnetic mechanism in which a suspended magnet moves within a water column near a coil. This system can generate a cycle-averaged power of 0.3 μW. The second system built and tested, i.e., a piezo-based harvester, offers more compatibility with in-ear devices and produces 0.2 μW on average. These two proposed harvesting systems prove that ear canal dynamic motion could be a genuine source of power for in-ear applications. By improving the proposed energy harvesters and continuing to reduce the power requirements of electronic devices, it is foreseeable in the near future that ear canal dynamic motion could at least partially and eventually fully supply the needed power for hearing devices, electronic hearing protectors, or any other electronic in-ear device.

ACKNOWLEDGMENT

The authors would like to thank Sonomax Technologies Inc. and its "Industrial Research Chair in In-Ear Technologies" for providing equipment for the experimental setups. They would also like to thank the five reviewers of this paper for their relevant comments and suggestions.

REFERENCES

[1] "Deafness and hearing impairment," World Health Organization, Geneva, Switzerland, Tech. Rep., Fact Sheet 300, 2010.

[2] S. Passerini, B. B. Owens, and F. Coustier, "Lithium-ion batteries for hearing aid applications: I. Design and performance," *J. Power Sources*, vol. 89, no. 1, pp. 29–39, Jul. 2000.

[3] U. Zink and G. Skuro, "Wireless battery charging system for existing hearing aids using a dynamic battery and a charging processor unit," U.S. Patent 6 498 455, Dec. 24, 2002.

[4] Y. Yang, Y. C. Liang, K. Yao, and C. K. Ong, "Low-power fuel delivery with concentration regulation for micro direct methanol fuel cell," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1470–1479, May/Jun. 2011.

[5] A. Lal and R. Duggirala, "Pervasive power: A radioisotope-powered piezoelectric generator," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 53–61, Jan. 2005.

[6] C. Lee and L. G. Frechette, "A silicon microturbopump for a rankine-cycle power generation microsystem—Part I: Component and system design," *J. Microelectromech. Syst.*, vol. 20, no. 1, pp. 312–325, Feb. 2011.

[7] N. Gòmez Estancona, A. G. Tena, J. Torca, L. Urruticoechea, L. Muñiz, D. Aristimuño, J. M. Unanue, and A. Urruticoechea, "Solar recharging system for hearing aid cells," *J. Laryngol. Otol.*, vol. 108, no. 09, pp. 768–769, Sep. 1994.

[8] R. W. Raimo and D. R. Howard, "Solar powered hearing aid," U.S. Patent 5 303 305, Apr. 12, 1994.

[9] S. Nam Cha, J.-S. Seo, S. M. Kim, H. J. Kim, Y.J. Park, S.-W. Kim, and J. M. Kim, "Sound-driven piezoelectric nanowire-based nanogenerators," *Adv. Mater.*, vol. 22, no. 42, pp. 4726–4730, Nov. 2010.

[10] K. Goto, T. Nakagawa, O. Nakamura, and S. Kawata, "An implantable power supply with an optically rechargeable lithium battery," *IEEE Trans. Biomed. Eng.*, vol. 48, no. 7, pp. 830–833, Jul. 2001.

[11] A. P. Sliski, M. T. Dinsmore, A. J. Boom, and N. T. Zervas, "Low power X-ray source with implantable probe for treatment of brain tumors," U.S. Patent 5 369 679, Nov. 29, 1994.

[12] V. Marian, B. Allard, C. Vollaire, and J. Verdier, "Strategy for microwave energy harvesting from ambient field or a feeding source," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4481–4491, Nov. 2012.

[13] M. C. Lei, L. Xie, and R. Du, "Kinematic analysis of an auto-winding system with the pawl-lever mechanism and its application in energy harvesting," *Int. J. Mech. Sci.*, vol. 52, no. 12, pp. 1605–1612, Dec. 2010.

[14] N. S. Shenck and J. A. Paradiso, "Energy scavenging with shoe-mounted piezoelectrics," *IEEE Micro*, vol. 21, no. 3, pp. 30–42, May/Jun. 2001.

[15] J. G. Rocha, L. M. Goncalves, P. F. Rocha, M. P. Silva, and S. Lanceros-Mendez, "Energy harvesting from piezoelectric materials fully integrated in footwear," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 813–819, Mar. 2010.

[16] J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo, "Biomechanical energy harvesting: Generating electricity during walking with minimal user effort," *Science*, vol. 319, no. 5864, pp. 807–810, Feb. 2008.

[17] L. C. Rome, L. Flynn, E. M. Goldman, and T. D. Yoo, "Generating electricity while walking with loads," *Science*, vol. 309, no. 5741, pp. 1725–1728, Sep. 2005.

[18] C. R. Saha, T. ODonnell, N. Wang, and P. McCloskey, "Electromagnetic generator for harvesting energy from human motion," *Sens. Actuators A, Phys.*, vol. 147, no. 1, pp. 248–253, Sep. 2008.

[19] J. P. Carmo, L. M. Goncalves, and J. H. Correia, "Thermoelectric microconverter for energy harvesting systems," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 861–867, Mar. 2010.

[20] A. Lay-Ekuakille, G. Vendramin, A. Trotta, and G. Mazzotta, "Thermoelectric generator design based on power from body heat for biomedical autonomous devices," in *Proc. IEEE Int. Workshop Med. Meas. Appl.*, May 2009, pp. 1–4.

[21] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 18–27, Jan. 2005.

[22] A. Delnavaz and J. Voix, "Energy harvester device for in-ear devices using earcanal dynamic motion," United States Provisional Patent Application 61/636,163, Apr. 20, 2012, filed through Protection Equinox.

[23] A. Khaligh, "Kinetic energy harvesting using piezoelectric and electromagnetic technologies—state of the art," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 850–860, Mar. 2010.

[24] E. Goll, H.-P. Zenner, and E. Dalhoff, "Upper bounds for energy harvesting in the region of the human head," *IEEE Trans. Biomed. Eng.*, vol. 58, no. 11, pp. 3097–3103, Nov. 2011.

[25] P. Qiao, H. Corporaal, and M. Lindwer, "A 0.964 mW digital hearing aid system," in *Proc. DATE*, Grenoble, France, 2011, pp. 1–4.

[26] Piezo film product type and price list, Meas. Spec. Inc., Hampton, VA, USA. [Online]. Available: www.meas-spec.com

[27] C. Sun, J. Shi, D. J. Bayerl, and X. Wang, "PVDF microbelts for harvesting energy from respiration," *Energy Environ. Sci.*, vol. 4, pp. 4508–4512, 2011.

[28] T. Starner, "Human-powered wearable computing," *IBM Syst. J.*, vol. 35, no. 3.4, pp. 618–629, 1996.

[29] A. Delnavaz and J. Voix, "Electromagnetic micro-power generator for energy harvesting from breathing," in *Proc. 38th IEEE IECON*, Oct. 2012, pp. 984–988.

[30] R. Dayal, S. Dwari, and L. Parsa, "Design and implementation of a direct AC–DC boost converter for low-voltage energy harvesting," *IEEE Trans. Ind. Electron.*, vol. 58, no. 6, pp. 2387–2396, Jun. 2011.

[31] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply," *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 669–676, Sep. 2002.

[32] R. J. M. Vullers, R. van Schaijk, I. Doms, C. Van Hoof, and R. Mertens, "Micropower energy harvesting," *Solid State Electron.*, vol. 53, no. 7, pp. 684–693, Jul. 2009.

Aidin Delnavaz received the B.S., M.S., and Ph.D. degrees from Sharif University of Technology, Tehran, Iran, in 2002, 2004, and 2010, respectively, all in mechanical engineering.

Since 2010, he has been with the Sonomax-École de Technologie Supérieure Industrial Research Chair in In-Ear Technologies (CRITIAS), Montreal, QC, Canada, where he is currently a Postdoctoral Researcher. He is currently working on energy harvesting for in-ear devices. His research interests include vibrations and microelectromechanical systems.

Jérémie Voix received the B.S. degree in fundamental physics from the Université des Sciences et Technologies de Lille, Villeneuve-d'Ascq, France, the M.S. degree in applied sciences in acoustics from the Université de Sherbrooke, Sherbrooke, QC, Canada, and the Ph.D. degree (with great distinction) from the École de Technologie Supérieure, Montréal, QC, Canada, for his work on the development of a "smart earplug."

In 2010, he joined the Department of Mechanical Engineering, École de Technologie Supérieure, as an Assistant Professor. Since 2000, he has worked concurrently in academic and industrial settings, publicized his fundamental and applied research results, and continued to register patents for an individual advanced hearing protection solution. He has authored or coauthored more than 60 scientific publications. One of his research areas is to merge hearing protection, hearing aid, and communication features inside a unique in-ear device, which is dubbed bionic ear.

Prof. Voix is an Elected Member of the Board of Directors of the Canadian Acoustical Association. He participates in a Canadian Standards Association committee and is an active Member of the American National Standard Institute.