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Ear canal dynamic motion as a source of power for in-ear devices

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Ear canal deformation caused by temporomandibular joint (jaw joint) activity, also known as “ear canal dynamic motion,” is introduced in this paper as a candidate source of power to possibly recharge hearing aid batteries. The geometrical deformation of the ear canal is quantified in 3D by laser scanning of different custom ear moulds. An experimental setup is proposed to measure the amount of power potentially available from this source. The results show that 9 mW of power is available from a 15 mm³ dynamic change in the ear canal volume. Finally, the dynamic motion and power capability of the ear canal are investigated in a group of 12 subjects. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4792307>]

I. INTRODUCTION

The human body is an abundant source of energy. Through body motion and body heat, energy can be harvested and used to power portable devices. The emergence of a new generation of portable low-power devices in recent years has given rise to a growing interest in energy harvesting technologies to meet the electrical power needs of these devices. The medical field is a promising sector for the use of these technologies because of the need to extend the energy availability in order to enable various forms of continuous therapy. Among the wearable or implantable medical devices currently existing, hearing aids account for one of the largest number of users. 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. These numbers encourage further investigation to use energy harvesting to power the electronic circuits of hearing aid devices. Moreover, recent developments are rendering these devices less energy consuming. Their typical power consumption has even dropped below 1 mW.² This means that several human activities as well as body heat can potentially power them. Still, there are several considerations and limitations for using energy harvesting for hearing applications. The different sources of passive human power and their capabilities to power hearing aids will be discussed in Sec. I A while the proposed source of power will be presented in Sec. I B.

A. Human body power sources

1. Upper limb motion

The maximum power generated by full bicep curls and arm lifts are estimated to be 24 W and 60 W, respectively.³ Obviously, only a small amount of this energy can be recovered to avoid inconveniencing the user. For example, the average power harnessed with a mechanical watch is 5 μ W while a flexible piezoelectric system at the elbows can generate up to 0.33 W.³

2. Walking

Walking is another human activity that has the largest associated energy. The available power during the normal walk can reach up to 67 W for a 68 kg male individual.³ This power can be scavenged during the heel strike, the kinematic motion of the knee, or indirectly by using the vertical movement of the body in a gravitational field while walking. However, the maximum amount of generated power is much less than the available power and is estimated to be 5 W for a knee mechanism⁴ and 7.3 W for a load backpack generator.⁵

3. 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 the human body and its environment. The greater the difference is, the more energy can be harvested. Considering the Carnot efficiency and the latent heat of vaporization, the available heat power ranges from 2.8 W to 4.8 W.⁶ Some sources estimate that the maximum recoverable power is 0.32 W in the neck³ and 2 mW in the head region.⁷

4. Breath

Breathing is another source of human body power that can be used for energy recovery purposes. During breathing, the air flows in and out of the respiratory system due to the pressure difference between lungs and the ambient air. The maximum breath pressure can reach up to 2% above the atmospheric pressure which corresponds to 1 W of power.³ A few micro-watts of this power can be successfully harvested through an appropriate electromagnetic mechanism.⁸ The obvious advantage of breathing as a source of power is its continuous nature, however the need for breathing masks would be too cumbersome for most users. Alternatively, there is an indirect way to generate power from breathing that is to fasten a tight band around the chest of the user. Such a mechanism can generate up to 0.83 W.³

5. Blood pressure and heartbeat

Assuming an average blood pressure of 100 mm of Hg (mercury), an energy rate of 0.93 W is quite possible from

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this source.³ For example, an intravascular turbine generator can generate up to $800\ \mu\text{W}$.⁹ In addition, a piezoelectric device can continuously recharge the batteries of the pacemakers by converting the vibrations from the heartbeats to electrical energy.¹⁰

6. Head motion

The human head is not as active as the legs and arms, but it can still be of interest for energy harvesting, particularly for implantable or wearable hearing applications. Goll *et al.* investigate energy harvesting in the region of the head.⁷ They categorize the mechanical energy of the head into four parts: periodic movements during exercise, transient movements during conversation, muscle force in macerating, and the pressure difference between the middle ear pressure and the ambient pressure. The estimated available power for each category considering a conservative scenario is 2 mW, $25\ \mu\text{W}$, $700\ \mu\text{W}$, and 150 pW, respectively.

Using the above-mentioned human body sources for powering hearing aids would be quite a challenge; because in the case of upper or lower limb motions, the site where the energy is harvested is distant from the ear, and the use of wiring would probably reduce the user's comfort. Using blood pressure for hearing applications is too risky, because it may increase the load on the heart. Harnessing the power generated by breathing or the mechanical energy of the head requires wearing certain visible instruments at the head region. This may not be acceptable for most users. Attaching thin thermoelectric modules to skin around the ear or at the region of the neck would seem to be more feasible, but it may still be unpleasant because of the reduced temperature at the location of the heat exchanger.

B. Proposed source of power

There is a source of kinetic energy in the human body which is not noticeably visible and has never been considered as a source of energy, but which shows great promise for in-ear applications. The ear canal is a dynamic environment, and when chewing, smiling, yawning, or speaking, the ear canal wall moves, expanding, and contracting. One can more easily perceive this movement by placing the auricular finger at the opening of the ear canal while opening and

closing one's mouth. In this paper, ear canal dynamic motion is studied to evaluate its capability to power hearing aids or other types of in-ear devices, such as smart hearing protectors, digital earplugs, Bluetooth communication earpieces, etc. An experimental setup is also constructed to measure energy recovery from the ear canal wall displacement. Since, the ear canal dynamic motion largely varies among individuals, its characteristics have been studied in a group of 12 subjects to estimate how much power is expected on average.

Section II discusses the ear canal shape and deformations. A test setup based on pressure transducers is presented in Sec. III in order to measure the power generated by the ear canal activity. The results from the statistical analysis of the ear canal dynamics is presented in Sec. IV. Finally, conclusions are drawn in Sec. V.

II. EAR CANAL SHAPE AND DEFORMATION

The human ear canal or *auditory meatus* is part of the auditory system. It transfers external sound to the tympanic membrane (TM) and mechanical structures of the middle ear. About two thirds of the ear canal is cartilaginous and soft, and the innermost third is surrounded by the mastoid bone as shown in Fig. 1(a). While the bony part of the ear canal hardly changes, the soft part is frequently deformed by temporomandibular joint (TMJ) excursion or movement. TMJ is the joint of the jaw bone. It is commonly referred to as the *jaw joint*. It connects the lower jaw bone or mandible to the temporal bone as illustrated in Fig. 1(b). During jaw movement (e.g., chewing), the mandible moves and the jaw joint rotates and translates. Since the jaw joint is located near the ear canal, its position can influence the ear canal shape and change its geometry. The extent of these changes varies significantly among individuals and has been statistically investigated in the literature to improve ear impression techniques required for the custom moulding of hearing aid shells.^{11–13}

A. Geometrical data acquisition

Understanding the nature of the changes and deformations in the ear canal requires geometrical data. Several methods have been reported in the literature to acquire a 3D geometry of the ear canal and study its shape, which is

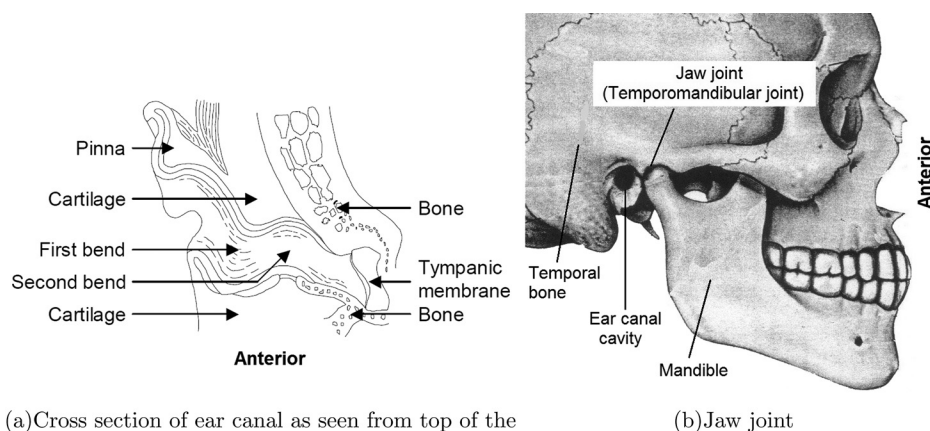


FIG. 1. Ear canal and jaw joint.

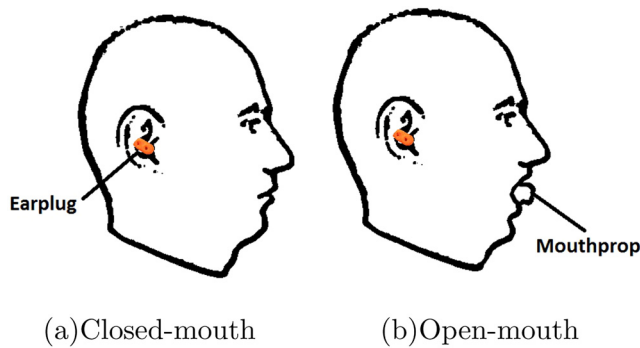


FIG. 2. Different mouth positions for the instant molding of the Sonomax custom earplug used to acquire ear canal geometry.

unique to each subject. For instance, silicon rubber moulds of the ear canal were made by using human cadavers, and a mechanical probe system has been used to obtain the complete geometry of ear canals.¹⁴ Another method to obtain the complete geometry of the ear canal was reported by Egolf.¹⁵ It was a computer assisted tomographic (CAT) scanner to make radiographic images of ear canal cross sections at constant intervals. Also, remote determination of ear canal geometry can be done by using magnetic resonance (MR) scanners.¹⁶ Finally, ear canal geometry can be obtained by laser scanning of ear impressions.¹⁷

The ear mould laser scanning procedure was adopted in this study in order to acquire geometrical data of the ear canal. The earplug used for this purpose is a re-usable custom earplug developed by Sonomax Technologies Inc. (sonomax.com). The custom earplug is fitted *in situ* into the user's ear within a few minutes.¹⁸ Since the most dynamic part of the ear is near the ear canal entrance and this is where the earplugs or hearing aids are usually fitted, the ear impressions in this location can reveal nearly all of the ear canal's dynamic behaviour. For this reason, two impressions were taken from the left ear of a healthy male individual; one in a closed-mouth and one in an open-mouth position as shown in Fig. 2. For the open-mouth position, a mouth prop was used between the front teeth to keep the mouth open at 20 mm maximum.

A comparison of these samples illustrates both extremes of the ear canal shape and will be discussed later in this section. The samples were then scanned by a 3D laser coordinate

measuring machine (CMM), their geometrical data were acquired in point clouds form, and imported to the MATLAB software (mathworks.com) for further processing.

B. Geometrical data analysis

The obtained earplug model originally included the concha portion (its extension beyond the ear canal and inside the concha bowl) as represented in Fig. 3(a). To trim this concha portion from the digital model, two boundary planes were assumed for each earplug, one at the distal end of the earplug near the tip and the other at the entrance point of the ear canal. The region between the *tip plane* and *entrance plane* represents the part of the ear canal filled by the earplug as illustrated in Fig. 3(b).

The mathematical representation of the ear canal geometry is based on the center axis method in which all geometrical characteristics are measured along the center axis curve. In this approach, the center axis is derived and the ear mould diameter is computed along the center axis. The center axis is the curve that passes through the ear canal and represents the center of the canal in each point. Three orthogonal unit vectors (orthonormal vectors) can be defined at each point: \hat{s} , \hat{n} , and \hat{b} . The first is tangent to the center axis, the second is perpendicular to the center axis and directs to the apparent origin of the curvature, and the third is perpendicular to both previous vectors as shown in Fig. 4(a).

The center of the canal in each point must be obtained by defining an appropriate cross section plane in that point. An appropriate cross section in each point is the section, which is perpendicular to the center axis, thus including \hat{b} and \hat{n} as demonstrated in Fig. 4(b). Therefore, there exists an iterative computational process to find both the curved center axis and cross section slices. One needs to know cross section slices to compute the center axis and have the center axis to form cross sections, so the iterative approach is used to find the center axis and cross sections, simultaneously.

The process to find the center axis and compute geometrical parameters in each section has been explained by Stinson.¹⁴ A somewhat similar approach is followed here except that:

- Instead of meshing the entire earplug space, each cross section is formed by the scattered points whose distances

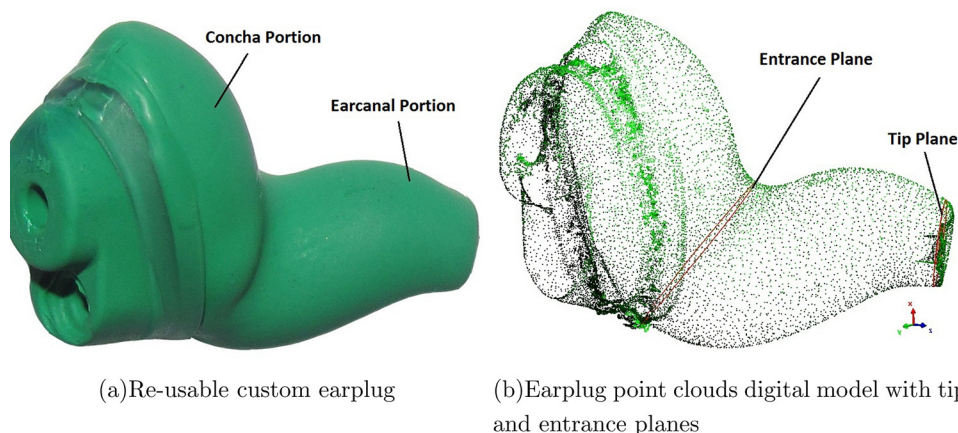


FIG. 3. Earplug model and border planes.

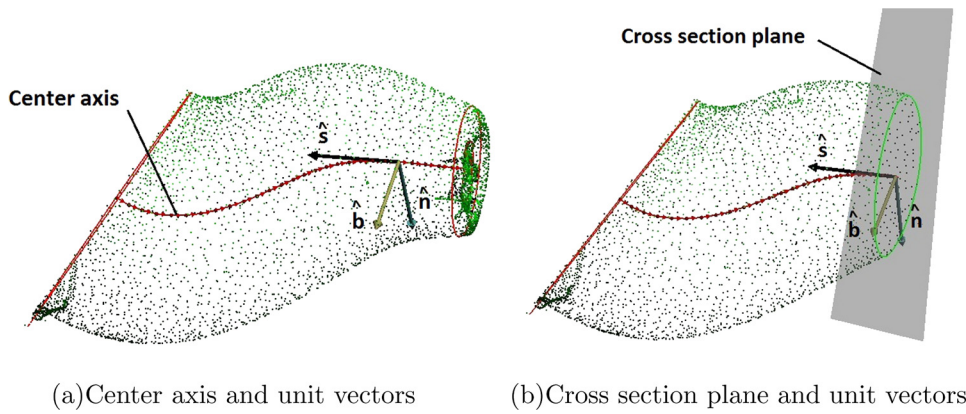


FIG. 4. Center axis method.

from the section in \hat{n} and \hat{b} plane lie in the range of ± 0.5 mm. In other words, the nearby points are projected to each cross section as represented in Fig. 5.

- Instead of defining a fixed point at the starting point of the center axis, it is assumed that it is perpendicular to the entrance plane. Also a fixed point is considered at the center of the tip plane as an endpoint of the center axis.

After about 10 iterations, the center axis converges to its final shape and geometrical parameters, such as diameter, curvature, torsion, and aspect ratio can then be computed along the center axis.

C. Geometrical characteristics of ear canal deformation

Ear canal deformation due to jaw joint position can be investigated by comparing the geometrical parameters of the ear canal at *closed-mouth* and *open-mouth* positions, because these represent two extremes of the jaw joint excursion. The obtained results are illustrated in Fig. 6(a), and the overlay of earplug scans at both positions is presented in Fig. 6(b).

Figure 6(a) shows that as we go towards the TM along the center axis, the ear canal diameter generally decreases. The ear canal typically has two bends that can be more or

less pronounced depending on the subject; the first bend is in the lateral part of the ear canal near the opening and the second bend is near the cartilage-bone junction (see, Fig. 1(a)). These two bends can be identified by the local maxima in the curvature plot. A transition between the first and second bends is accompanied by sudden changes in the direction of curvature, hence creating a sharp peak in the torsion plot. In general, the shape of the cross section slices can be quite different: some cross sections are nearly circular, while others are elliptical or oval. To quantify the cross section shapes, the aspect ratio is defined as the ratio of the minor axis to the major axis; the closer this is to unity, the more circular the cross section is.

By opening the mouth, the jaw joint moves forward, pulls the cartilage at the entrance of the ear canal, expanding the canal at the first bend, and compressing it at the second bend region as illustrated in Fig. 6. Consequently, ear canal volume increases at the first bend and decreases at the second bend. The volume changes are $+15 \text{ mm}^3$ and -70 mm^3 for the first and second bend regions, respectively. Changes are not limited to the ear canal volume; other geometrical parameters also change. For example, the aspect ratio tends towards unity in the open-mouth position, meaning that the ear canal cross sections become more circular when the mouth is open.

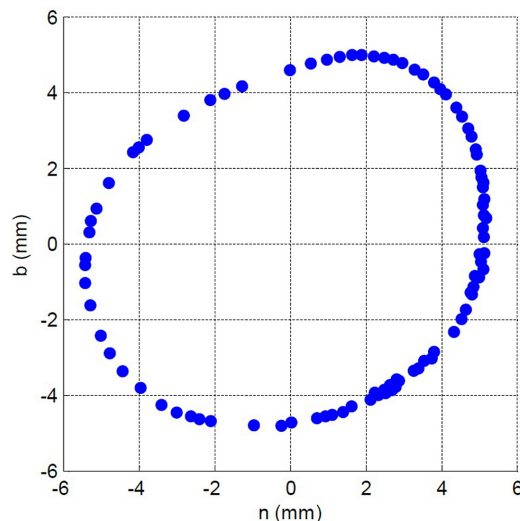


FIG. 5. Projected points in the cross section plane at $s = 3.7$ mm from the entrance plane.

III. POWER CAPABILITY OF EAR CANAL DYNAMIC MOTION

In relation to the ear canal, jaw displacement deforms its shape and changes its volume. The power which can be produced from this type of dynamic action depends on how much volume is displaced and how fast it occurs. An experimental setup is proposed to study the dynamic behaviour of the ear canal and evaluate its power capability, as shown in Fig. 7. The setup is a hydraulic system that translates the volume variations within the ear canal into height variations in a water column within a plastic tube. These variations are measured by a pressure transducer. The sensitivity of the pressure transducers usually depends on their pressure range and maximum pressure reading. Since the working pressure in the proposed hydraulic system is a great deal higher than the pressure variation, two water columns and two pressure transducers are used: one for measuring the basic or reference pressure (P_r) that is required to inflate the earplug and

one for measuring the fine fluctuations (P_d) that are created by jaw joint activity.

In order to perform the test, the earplug and tubes are filled with water, air bubbles are completely removed, and the system is checked for leaks. The earplug is carefully positioned inside the ear at the first bend region and water is pumped into the system until the reference water column pressure reaches $P_r = 13$ kPa. At this pressure level, a full contact between the earplug and ear canal walls is obtained.¹⁹ The reference column is then locked by closing the shut-off valve. After setting the reference pressure, the ear canal is deformed by the test subject by repeatedly opening and closing the mouth. As ear canal volume changes, the water level in the main column rises and falls, while the reference column remains at a constant height. Thus, the differential pressure sensor, placed between the main and the

reference water columns, can accurately measure the pressure differences (P_d). The total pressure in the main column can then be calculated by summing up the output of differential and gauge pressure sensors ($P = P_r + P_d$).

The total pressure for various jaw joint activities such as the subject's articulating of "one," "two," "three," "four," and "five" using a normal voice volume, wide opening followed by rapid closing, and successive opening and closing of the mouth is shown in Fig. 8(a). Pressure changes are obvious for all activities except saying the words "two" and "three" in which the mouth does not open as wide.

The instantaneous available power (W_{av}) from jaw joint movement can be estimated by

$$W_{av} = \frac{AP}{\rho g} \left| \frac{dP}{dt} \right| \quad (1)$$

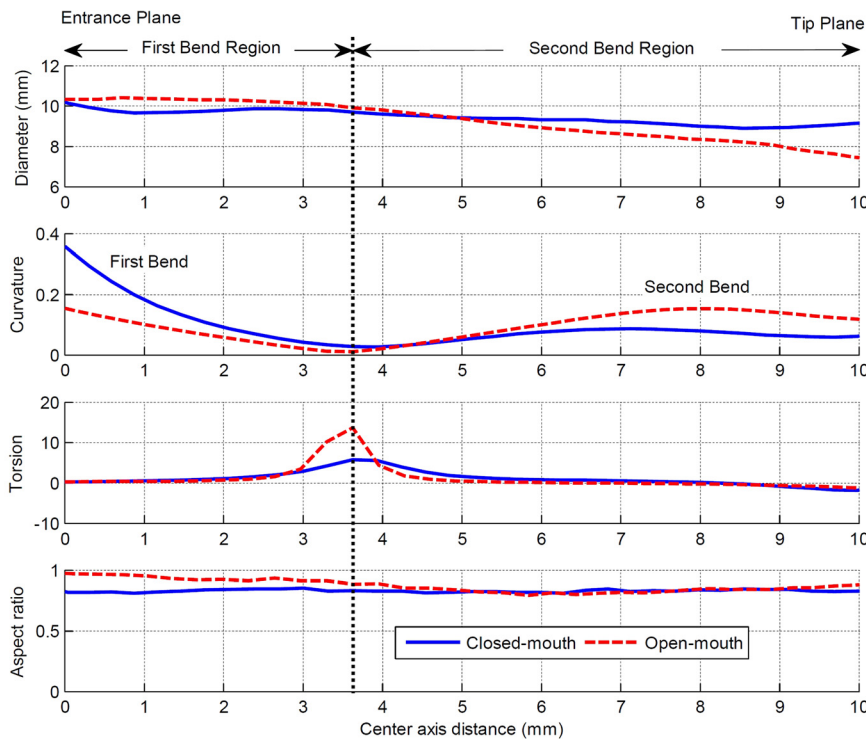
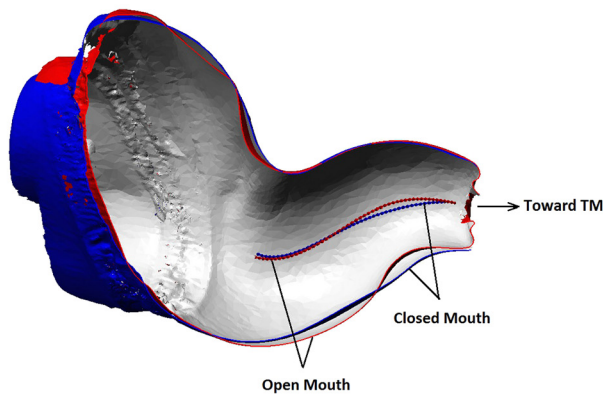


FIG. 6. Earplug geometries in "open mouth" and "closed mouth" positions.

(a) Ear canal geometry parameters including diameter, curvature, torsion and aspect ratio as a function of distance along the center axis curve



(b) Earplugs overlay

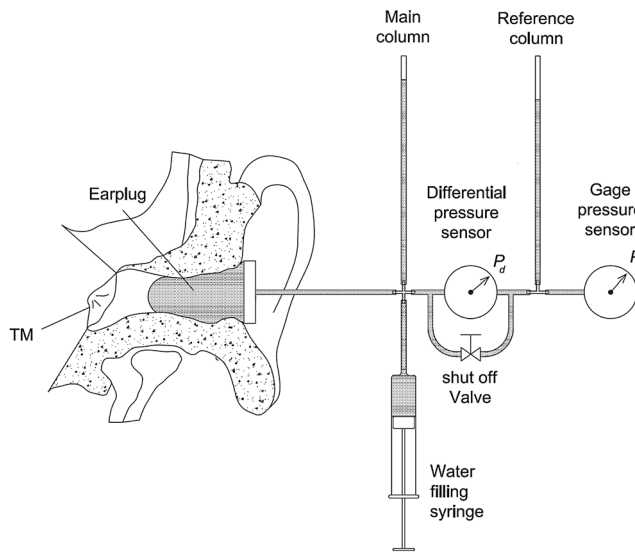


FIG. 7. Schematic representation of the setup used to evaluate the power capability of ear canal dynamic deformation.

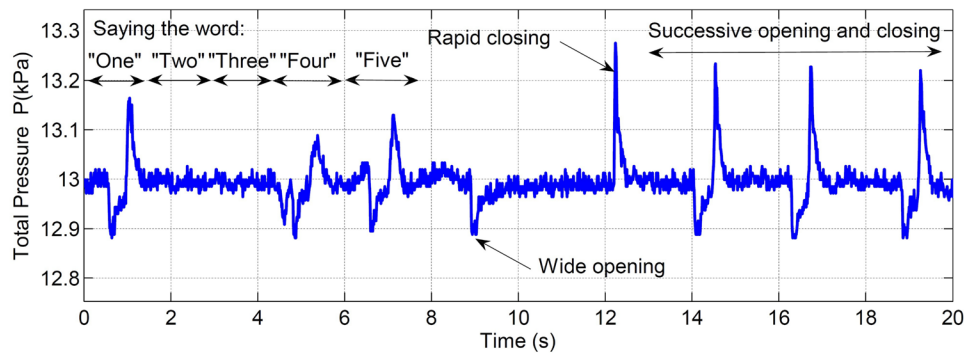
in which A is the cross section area of the tube, ρ is the water density, g is the gravitational acceleration, P is the total pressure in Pa , and dP/dt is the rate of the pressure change in the main water column and can be calculated by differentiating from the data in Fig. 8(a). The instantaneous available power from previously mentioned jaw joint activities is presented in Fig. 8(b). This figure also shows that the maximum available power is 9 mW.

This maximum power value represents the available mechanical power and does not necessarily reflect the amount of power that will be harvested in practice by a given energy harvester and this for two reasons. First, and most importantly, the efficiency of any physical micro-energy harvesting device, such as the device developed by the authors,²⁰ implies a loss of mechanical and electrical energy, meaning that in practice, its efficiency is less than 100%. Second, even if a micro-energy harvester's losses could be minimized and its efficiency maximized, such a device might also induce an increase of mechanical stiffness, leading to some discomfort to the wearer.

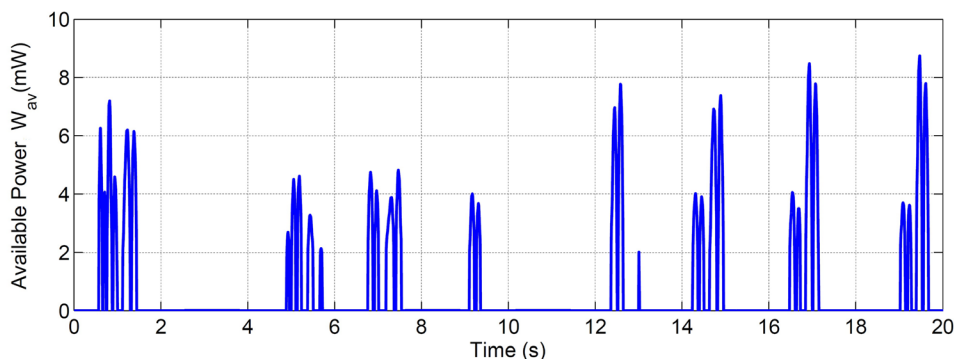
While this second argument holds true, it should be noted that the earplug used in this research project is made of soft medical-grade silicone rubber that does not create excessive localized pressure to the ear canal walls. Even if it is equipped with the envisioned micro-harvesting device, as long as its overall stiffness does not exceed the rigidity of harder earpieces used in hearing aid industry,²¹ it is not likely to cause the discomfort issues. It is, therefore, reasonable to assume that potential discomfort is not a major issue compared to improving the efficiency of such devices.

IV. EAR CANAL DYNAMICS VARIATIONS

The results which have been presented so far are limited to one ear canal, while the ear canal shape and activity is assumed to vary among individuals. Therefore, the influence of jaw joint movement on the ear canal volume is investigated in this section for a group of 12 subjects. The group



(a) Variation of the total pressure in the main column as a function of jaw joint activities



(b) Available power computed from the different jaw joint activities

FIG. 8. Ear canal dynamic experimental results.

was composed of 3 female and 9 male subjects with age ranging from 23 to 60 years old. The test procedure is the same as the one described in Sec. II A and the moulding of all custom earplugs was performed by a Sonomax trained technician in order to obtain consistent earplug impressions for all subjects. Four pairs of earplugs were made in total from each subject, two pairs in the “closed-mouth” and two pairs in the “open-mouth” positions. The average of ear canal volume changes for each subject was then calculated, and the results are presented in Fig. 9.

In this figure, the ear canal changes in volume at the first and second bends are divided in several bins, and the number of earplugs in each bin is demonstrated. The negative sign signifies a decrease in the ear canal volume while opening the mouth. The distribution of the bars in this figure clearly shows the diversity of ear canal volume changes due to jaw joint movement. The details of these changes are presented in Table I. In this Table, L and $|\Delta V|$ indicate the length and the absolute volume changes of ear canals, respectively. Group “00L” represents the first subject for which the available power was previously measured in Sec. III. As shown in this section, up to 9 mW of power is available when there is a 15 mm³ variation in the ear canal volume at the first bend region.

The available power for other subjects can be estimated based on the experimental results for the first subject. According to Eq. (1), the available power depends on the rate of the pressure change in the proposed hydraulic setup, hence the following chain of proportionality can be derived:

$$W_{av} \propto \left| \frac{dP}{dt} \right| \propto \left| \frac{\Delta P}{\Delta t} \right| \propto |\Delta V|f \quad (2)$$

in which f is the frequency of mouth opening and closing cycle and it depends on the type of jaw activities as well as the subject himself. However, in a constant frequency of jaw activities, the available power becomes only proportional to the absolute volume changes of the ear canal. Now, by comparing the experimental results for the first subject with $|\Delta V|$'s reported in Table I, one can easily estimate how

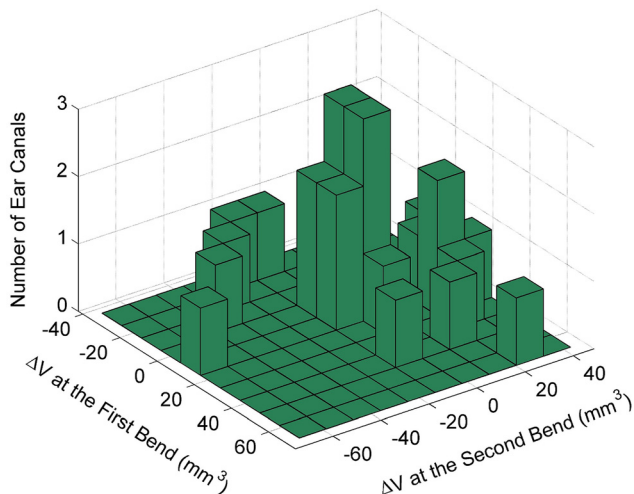


FIG. 9. Histogram of the volume changes at the first and second bend regions.

TABLE I. Ear canal volume changes between open-mouth and closed-mouth positions (“*” indicates the experimental measurement).

Subject	Sex	Age	First bend			Second bend		
			L (mm)	$ \Delta V $ (mm ³)	W_{av} (mW)	L (mm)	$ \Delta V $ (mm ³)	W_{av} (mW)
00L	M		3	15	9*	7	70	42
01L	F		4	37	22	7	13	8
01R		25	3	31	18	5	16	9
02L	F		3	1	1	5	3	2
02R		34	4	3	2	6	9	5
03L	M		5	1	1	8	8	4
03R		24	5	25	15	7	30	18
04L	M		4	11	6	5	29	17
04R		25	4	6	3	7	7	4
05L	M		2	18	10	7	4	2
05R		33	4	25	15	5	29	17
06L	M		5	39	23	5	13	7
06R		26	4	34	20	8	26	15
07L	M		4	6	3	4	9	5
07R		28	6	69	41	4	22	13
08L	M		3	10	6	7	0	0
08R		28	3	22	13	7	33	19
09L	F		2	17	10	7	29	17
09R		23	3	1	1	7	9	5
10L	M		5	39	23	5	12	7
10R		35	6	13	7	6	8	4
11L	M		5	11	6	7	9	5
11R		28	3	2	1	6	43	25
12L	M		4	10	6	5	41	24
12R		60	5	1	1	6	1	1
Mean		31	4	17.7	10.6	6.1	19.3	11.5
Std. dev.		10	1.1	16.6	9.9	1.2	17.6	10.5

much power is expected from each ear canal at the frequency equal to the experiment of the first subject. These estimations are given in columns 5 and 8 of the Table. The maximum available power averaged over subjects is 10.6 mW and 11.5 mW for the first and the second bends, respectively. Also the maximum available power of at least 5 mW can be observed for all subjects.

V. CONCLUSIONS AND FUTURE WORK

The idea behind this study was to introduce ear canal dynamic motion as a new source of human body generated power for in-ear devices. The geometrical analysis of the ear canal showed a 15 mm³ change in volume for a typical ear canal as a result of jaw joint movement. This change of volume was translated into a change of water level within a vertical tube in order to measure its power. The instantaneous available power was then estimated to peak at 9 mW when the mouth was opened and closed. The wide diversity of the ear canal dynamics was also observed among 12 subjects. However, the maximum available power in average is estimated to be more than the measured experimental value.

If only a little percentage of this available power can be successfully harnessed, the authors assume that it would be possible to fully or at least partially supply the needed power of hearing devices.

As a future research stride, jaw joint activities should be studied as to the regular day-to-day lives of each individual, in order to have a better estimation of the potential energy capability of jaw joint activity. Additionally, some energy harvesting systems based on the electromagnetic or piezoelectric energy conversion will be designed and tested to obtain energy from the ear canal dynamic motion.

ACKNOWLEDGMENTS

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