



Piezoelectric Micro-Energy Harvesting from Ear-Canal Mechanical Motion for Hearing-Aid Power Support

A Physics-Based Review, Theoretical Framework, and Conceptual Engineering Design

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Abstract: Miniature hearing aids operate under severe constraints in volume, mass, battery capacity, acoustic performance, moisture resistance, and user comfort. This paper investigates whether otherwise dissipated mechanical motion associated with the ear canal and temporomandibular joint can be converted into supplementary electrical energy by piezoelectric transduction. The study uses a physics-based contemporary review and conceptual engineering analysis. Direct piezoelectric constitutive relations, transducer capacitance, open-circuit voltage, time-varying power, mechanical strain energy, resonance, acoustic intensity, storage energy, and end-to-end efficiency are used to establish a quantitative framework. Published in-ear studies demonstrate that jaw-related ear-canal deformation is a measurable mechanical energy source and that flexible PVDF structures can generate electrical output in the microwatt range under defined conditions. A free-field acoustic calculation also shows why ordinary sound alone is a weak source for a hearing-aid-sized capture area. Literature from 2024-2026 emphasizes flexible PVDF-based harvesters, mechanically amplified structures, MEMS integration, and ultra-low-power power-management circuits. The proposed architecture combines a compliant piezoelectric transducer, low-loss rectification, energy buffering, an ultra-low-power power-management unit, and micro-storage or an auxiliary load. The analysis does not support continuous full self-powering of the hearing aid; the more defensible near-term application is battery support, gradual energy accumulation, or intermittent operation of low-power auxiliary electronics. The governing physics establishes plausibility, while experimental validation remains necessary to determine the net energy benefit in a real device.

Keywords: piezoelectric energy harvesting; ear-canal dynamic motion; hearing aid; renewable-energy physics; PVDF; PZT; ultra-low-power electronics.

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Nomenclature

Symbol	Meaning / unit
A	Active or acoustic capture area (m ²)
C _p	Piezoelectric capacitance (F)
D	Electric displacement (C/m ²)
d	Piezoelectric coefficient (C/N or m/V, depending on form)
E	Electric field (V/m)
E _{cap}	Energy stored in capacitor (J)
F	Mechanical force (N)
f _n	Natural frequency (Hz)
I, i(t)	Current / instantaneous current (A)
I _{ac}	Acoustic intensity (W/m ²)
k _{eff}	Effective stiffness (N/m)
L _p	Sound-pressure level (dB SPL)
P, $\bar{P}$	Power / average power (W)
Q	Electric charge (C)
R _l	Electrical load resistance (Ω)
S	Mechanical strain (-)
T	Mechanical stress (Pa)
V, v(t)	Voltage / instantaneous voltage (V)
ϵ	Permittivity (F/m)
η	Efficiency (-)
ρ	Air density (kg/m ³)
ω	Angular frequency (rad/s)

1. Introduction

Energy harvesting converts small environmental or biomechanical energy flows that would otherwise be dissipated into useful electrical energy. In renewable-energy physics, the importance of this concept is not that it competes with photovoltaic, wind, or grid-scale generation; rather, it reduces dependence on stored electrochemical energy at the point of use. This distinction is especially important for miniature electronics, where even tens of microwatts can matter if they are accumulated over time or allocated to an intermittent function. Recent reviews describe mechanical and piezoelectric harvesting as a practical route for low-power wearable and biomedical systems, while also emphasizing that miniaturization, irregular human motion, packaging, and power-management losses prevent simplistic claims of battery replacement (Ali et al., 2024; Almarri et al., 2024; Ahmad, 2026).

Hearing aids provide a demanding test case. A modern in-ear device must preserve acoustic gain, signal processing, wireless functions, sealing, comfort, reliability, and moisture resistance within a very small envelope. Increasing battery volume is therefore not always attractive. The alternative investigated here is to recover a fraction of mechanical energy generated by normal in-ear motion, particularly changes in ear-canal geometry associated with jaw movement. Direct studies by Delnavaz and Voix and later investigators established that this motion is measurable and mechanically energetic, while a flexible piezoelectric earpiece demonstrated direct electrical conversion in an in-ear form factor (Delnavaz & Voix, 2013a, 2013b, 2014; Bouchard-Roy et al., 2020).

Free acoustic sound and local ear-canal mechanical deformation are physically distinct energy sources and should not be treated as equivalent. Sound harvesting begins

with pressure fluctuations in air and generally requires an intermediate diaphragm or resonant structure to generate mechanical strain. Jaw-related ear-canal motion, by contrast, is already a localized mechanical deformation that can directly strain a piezoelectric element. For this reason, the proposed application is analyzed primarily as a mechanical energy-harvesting problem, while acoustic harvesting is retained as a comparison case. The distinction affects the available-energy calculation, transducer design, coupling mechanism, and interpretation of published results.

This work is a contemporary literature review, theoretical physics analysis, and conceptual system design. Its central contribution is to connect application-specific in-ear evidence with the governing equations of piezoelectricity and micro-energy conversion. The equations identify the physical conditions and parameters that control charge generation, voltage, energy transfer, and usable power. Because the study does not report original laboratory measurements, the analysis is used to establish theoretical plausibility and design requirements rather than experimental proof. Validation of a specific hearing-aid implementation requires direct measurement of ear-canal strain, transducer impedance, rectifier loss, storage behavior, and net delivered energy.

2. Research Problem, Questions, and Contributions

2.1 Research problem

The research problem is to determine whether small, irregular mechanical deformations occurring in and around a hearing aid can be converted into a net useful electrical contribution without imposing a larger penalty in stiffness, volume, acoustic performance, circuit losses, or user discomfort. The difficulty is fundamentally an energy-balance problem: the source is intermittent, the piezoelectric element is capacitive, the interface has thresholds and leakage, and the energy ultimately delivered to storage must exceed the energy consumed by the added electronics.

2.2 Research questions

1. What physical relationships govern conversion of ear-canal deformation into piezoelectric charge, voltage, energy, and power?
2. How does the available mechanical source compare with free-field acoustic energy at a hearing-aid-sized capture area?
3. Which material platform, particularly PZT, PVDF, or a MEMS structure, provides the best system-level compromise for in-ear integration?
4. What published electrical outputs and mechanical source powers define a realistic order of magnitude?

5. What power-management architecture can preserve useful energy when the source is intermittent and low power?
6. Can the mechanism realistically replace the main hearing-aid battery, or is battery support a more defensible objective?

2.3 Contributions of this paper

- Defines the proposed hearing-aid application as a physics-led micro-energy-harvesting problem governed by mechanical coupling, piezoelectric conversion, and end-to-end energy balance.
- Introduces the full linear piezoelectric constitutive equations rather than relying only on $Q = dF$.
- Develops a simplified electrical model linking force variation, transducer capacitance, excitation frequency, load resistance, and maximum resistive power.
- Uses acoustic intensity physics to quantify why free sound alone is a weak energy source over a miniature area.
- Synthesizes direct in-ear evidence with 2024-2026 reviews of wearable harvesters, materials, and biomedical power management.
- Defines a falsifiable experimental pathway based on net stored energy rather than open-circuit voltage.

3. Review Method and Evidence Hierarchy

The literature review focused on peer-reviewed studies addressing ear-canal dynamic motion, in-ear piezoelectric harvesting, piezoelectric material physics, low-frequency vibration harvesting, and ultra-low-power power-management circuits. Priority was given to original publisher records and peer-reviewed articles from IEEE, Elsevier, ACS, Wiley, AIP, IOP, and MDPI, with particular emphasis on direct in-ear evidence and recent work through 2026 where relevant. Studies were assessed according to the physical energy source, transducer material and geometry, mechanical coupling, reported electrical or mechanical output, and relevance to hearing-aid-scale integration. The review is structured and critical but is not presented as a formal PRISMA systematic review.

Evidence was ranked by proximity to the proposed application. The strongest tier contains direct measurements of ear-canal dynamic motion and in-ear harvesting prototypes. The second tier contains wearable and biomedical piezoelectric studies that clarify material or mechanical design. The third tier contains power-management and energy-storage literature relevant to microwatt-scale systems. Acoustic-harvesting studies are included as comparison evidence, not as a direct substitute for in-ear mechanical measurements. This hierarchy prevents a common error in energy-harvesting papers: transferring a voltage obtained under a high-intensity

laboratory source directly to an unrelated wearable environment.

4. Physics of Piezoelectric Energy Conversion

4.1 Linear constitutive equations

The direct piezoelectric effect is an electromechanical coupling phenomenon in non-centrosymmetric materials. A physically complete linear description couples mechanical strain and stress to electric field and electric displacement. In stress-charge form, the constitutive equations may be written as (He & Briscoe, 2024; Pan et al., 2024):

$$S = s^E T + d^T E \quad (1)$$

$$D = d T + \varepsilon^T E \quad (2)$$

Here S is the strain vector, T is the stress vector, s^E is elastic compliance measured at constant electric field, d is the piezoelectric coupling matrix, E is electric field, D is electric displacement, and ε^T is permittivity at constant stress. The tensor form matters because a thin PVDF strip in bending, a PZT plate in compression, and a MEMS cantilever do not use the same effective coefficient or strain field. The material coefficient alone therefore cannot predict harvested energy; geometry and boundary conditions determine which piezoelectric mode is activated.

4.2 From stress to charge, current, and voltage

For a simplified uniaxial case with approximately uniform effective stress, the familiar force-charge relation can be recovered as an engineering approximation:

$$Q \approx d_{\text{eff}} F \quad (3)$$

This equation is useful for intuition, but it is not a complete harvester model. The electrode charge is more generally obtained from the electric displacement field:

$$Q = \int_a D \cdot n \, dA \quad (4)$$

Because useful electrical output requires changing charge, the instantaneous source current is related to the time derivative of charge:

$$i_p(t) = dQ/dt \quad (5)$$

If the simplified relation $Q = d_{\text{eff}} F$ is used and $F(t)$ varies with time, then $i_p(t) \approx d_{\text{eff}} dF/dt$. This immediately gives an important physics result: a static force can create a charge redistribution and voltage, but continuous power requires changing mechanical deformation. The harvester therefore depends on motion cycles, not merely on static fit pressure inside the ear.

A piezoelectric layer also behaves electrically as a capacitor. For a parallel-electrode approximation:

$$C_p \approx \varepsilon A / t \quad (6)$$

where A is electrode area and t is active-layer thickness. In an open-circuit approximation, the voltage scale is:

$$V_{oc} \approx Q / C_p \quad (7)$$

Equations (3), (6), and (7) show why large open-circuit voltage is not synonymous with large energy. A small capacitance can produce a high voltage from a small amount of charge. For energy harvesting, matched-load power or stored energy is a more meaningful metric than voltage alone.

4.3 Simplified load-matching model

A useful first-order model represents the piezoelectric element as a current source in parallel with its capacitance C_p . If the force is sinusoidal, $F(t) = F_0 \sin(\omega t)$, the current-source amplitude under the simplified force-charge relation is $I_0 = d_{\text{eff}} F_0 \omega$. For a purely resistive load R_L connected directly across this ideal source-capacitance pair, the average resistive power is:

$$\bar{P}_1 = I_0^2 R_L / [2(1 + (\omega R_L C_p)^2)] \quad (8)$$

Differentiating Equation (8) with respect to R_L gives the ideal resistive matching condition:

$$R_{\text{opt}} = 1 / (\omega C_p) \quad (9)$$

and the corresponding idealized maximum resistive power:

$$\bar{P}_{\text{max}} = I_0^2 / (4 \omega C_p) \quad (10)$$

These equations are not used to predict the final hearing-aid output because the actual ear motion is not sinusoidal and the interface is not a simple resistor. They are included because they expose the controlling physics. Output depends on the rate of force change, excitation frequency, capacitance, and electrical load. A circuit designed without measuring the source impedance can therefore lose much of the available energy even if the piezoelectric material itself is efficient.

4.4 Mechanical energy and frequency response

The mechanical energy available to a piezoelectric element depends on the stress-strain field. In linear elasticity the recoverable strain-energy density integrates to:

$$U_m = \frac{1}{2} \int_v T : S \, dV \quad (11)$$

For a simple lumped spring, this reduces to $U = \frac{1}{2} kx^2$. If a resonant structure is used, its approximate natural frequency is:

$$f_n = (1 / 2\pi) \sqrt{(k_{\text{eff}} / m_{\text{eff}})} \quad (12)$$

Conventional vibration harvesters often obtain high output by tuning resonance to a nearly periodic source. Human jaw motion is low-frequency, irregular, and user dependent, so a narrow high-Q resonator may miss much of

the available spectrum. Recent work therefore emphasizes compliant structures, mechanical amplification, bistability, frequency up-conversion, and broadband approaches for wearable sources (Radeef et al., 2025; Ahmad, 2026). Avetissian et al. (2024), for example, explored a hydraulic coupling and bistable resonator specifically to transform slow ear-canal motion into more favorable piezoelectric excitation.

4.5 Power, energy storage, and end-to-end efficiency

For any electrical port, instantaneous power is $p(t) = v(t)i(t)$, and average power over an interval T is:

$$\bar{P} = (1/T) \int_0^T v(t)i(t) dt \quad (13)$$

The energy accumulated in a storage capacitor is particularly useful experimentally because it avoids ambiguity associated with pulsed waveforms:

$$E_{cap} = \frac{1}{2} C V^2 \quad (14)$$

$$\Delta E_{cap} = \frac{1}{2} C (V_2^2 - V_1^2) \quad (15)$$

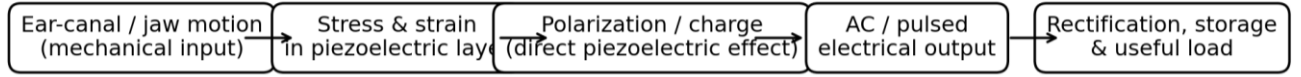
A transparent end-to-end efficiency definition is then:

$$\eta_{e2e} = E_{useful} / E_{mech} \quad (16)$$

At system level, the net energy is reduced by mechanical coupling, piezoelectric conversion, rectification, DC-DC conversion, leakage, and storage losses. It is therefore useful to think of the efficiency as a chain rather than a single material number:

$$\eta_{sys} \approx \eta_{coup} \cdot \eta_{piezo} \cdot \eta_{rect} \cdot \eta_{PMU} \cdot \eta_{store} \quad (17)$$

This equation explains why a high-performance PZT specimen can still yield a poor wearable system if its stiffness prevents strain transfer, and why an excellent rectifier is irrelevant if its quiescent current exceeds the harvested average current.



Physics chain: mechanical energy is not created; a fraction is converted and conditioned for storage/use.

Figure 1. Physics-based energy-conversion chain for the proposed in-ear harvester. Author's conceptual representation based on the reviewed literature.

5. Why Free Acoustic Energy Is a Weak Primary Source

Unwanted sound vibrations can excite piezoelectric structures, but the available free-field acoustic power over a miniature area is limited by basic acoustics. For a plane progressive wave in air, sound-pressure level is related to rms acoustic pressure by:

$$L_p = 20 \log_{10}(p_{rms} / p_{ref}), \quad p_{ref} = 20 \mu\text{Pa} \quad (18)$$

The corresponding time-averaged acoustic intensity is approximately:

$$I_{ac} = p_{rms}^2 / (\rho c) \quad (19)$$

and the incident acoustic power on area A is:

$$P_{ac} = I_{ac} A \quad (20)$$

Using $\rho = 1.21 \text{ kg/m}^3$, $c = 343 \text{ m/s}$, and an illustrative capture area of 1 cm^2 , the theoretical incident power values in Table 1 are obtained. These are source powers before any diaphragm, mechanical, piezoelectric, rectification, or storage loss. The calculation is intentionally generous because a real hearing-aid structure will not absorb all incident acoustic energy.

Table 1. Theoretical free-field acoustic power incident on a 1 cm^2 area

SPL	p_{rms}	Intensity	Incident power on 1 cm^2
60 dB	0.02 Pa	$9.64\text{e-}07 \text{ W/m}^2$	0.0964 nW
80 dB	0.2 Pa	$9.64\text{e-}05 \text{ W/m}^2$	9.64 nW
96 dB	1.26 Pa	0.00384 W/m^2	384 nW
100 dB	2 Pa	0.00964 W/m^2	964 nW

At 100 dB SPL, the incident free-field power on 1 cm^2 is still only about $0.96 \mu\text{W}$ before conversion losses. At 80 dB it is about 9.6 nW. This order-of-magnitude result does not invalidate acoustic harvesters that use resonators or larger effective apertures, but it shows why free ambient sound is not a strong basis for claiming tens of microwatts from a hearing-aid-sized area. It also explains why direct mechanical deformation of an in-ear earpiece is a more physically promising source for the proposed application. High sound-pressure levels should not be proposed merely to increase harvested energy because hearing safety and the primary function of the device take precedence.

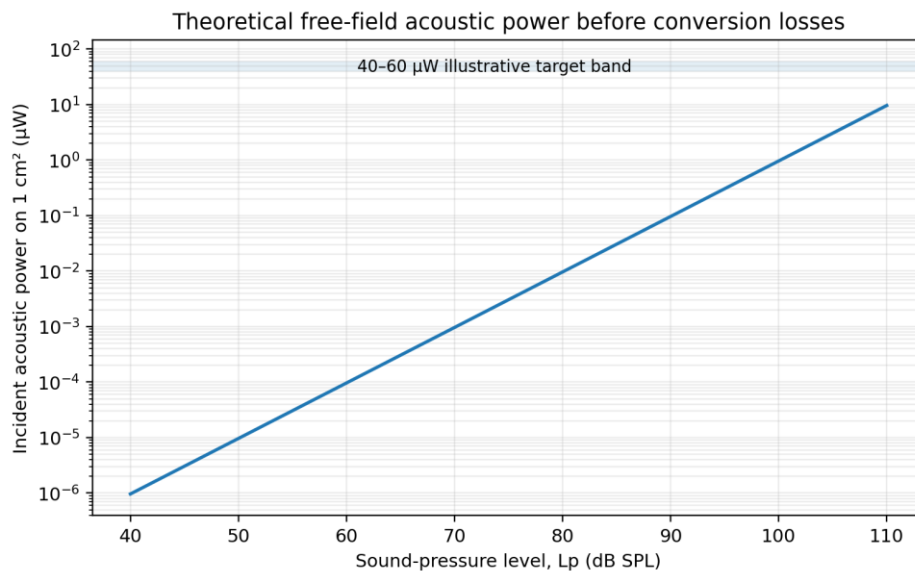


Figure 2. Theoretical incident free-field acoustic power versus sound-pressure level for a 1 cm² capture area. The shaded band marks an illustrative 40–60 µW engineering target; conversion losses are not included.

6. Ear-Canal Mechanical Motion as the Relevant Energy Source

The ear canal is not mechanically static. Motion of the temporomandibular joint during speaking, chewing, and mouth opening changes canal geometry and can deform an earpiece. Delnavaz and Voix (2013a) quantified ear-canal dynamic motion as a potential power source, and their later work demonstrated a flexible PVDF piezoelectric earpiece that converted this deformation to electrical energy (Delnavaz & Voix, 2013b). Subsequent studies investigated deformation modes, source power across participants, and

alternative mechanical transfer structures (Carioli et al., 2016; Bouchard-Roy et al., 2020; Avetissian et al., 2024).

The key distinction is between source power and harvested electrical power. Bouchard-Roy et al. (2020) reported mean mechanical source power on the order of tens of milliwatts during mastication in their measurement framework, while the flexible piezo-earpiece of Delnavaz and Voix (2013b) reported average electrical power of approximately 70 µW under its study conditions. The difference is not a contradiction. Only a small portion of the mechanical energy can be extracted without disturbing natural motion, and additional losses occur in strain transfer, transduction, electrical loading, rectification, and storage.

Table 2. Selected evidence directly relevant to in-ear energy harvesting

Study	Evidence type	Reported quantity	Physics significance
Delnavaz & Voix (2013a)	Ear-canal source characterization	Mechanical source quantified from dynamic ear-canal motion	Establishes that jaw-related canal deformation contains recoverable mechanical energy.
Delnavaz & Voix (2013b)	Flexible PVDF piezo-earpiece	44 µJ per jaw cycle; ~70 µW average in the reported experiment	Direct electrical proof-of-concept in a compliant in-ear geometry.
Delnavaz & Voix (2014)	In-ear generator concepts	Mechanical and generator-level energy analysis	Shows the large gap between source energy and practical electrical recovery.
Carioli et al. (2016)	Deformation-mode analysis	Bending contribution reported to exceed radial compression on average	Supports physics-led placement and geometry optimization.
Bouchard-Roy et al. (2020)	Human source-power measurement	Mean source power 26.2 mW across six participants while eating	Confirms activity- and user-dependent source availability; not electrical output.
Avetissian et al. (2024)	Hydraulic/bistable piezoelectric concept	~13 µW baseline predicted value for mastication cycle in reported model	Illustrates mechanical amplification and the complexity of practical transfer mechanisms.
Salemi et al. (2024)	CT-based ear-canal model + finite-element/speaking-motion analysis	Modeled piezoelectric voltage and AC-to-DC power for several speaking activities	Recent application-specific modeling; useful for hypothesis refinement but not a substitute for measured harvested power.

The most important conclusion from Table 2 is not a single output number. It is that the proposed mechanism has a physically measured source and at least one direct piezoelectric in-ear demonstration, but performance varies strongly with geometry, activity, user anatomy, and interface architecture. A journal-quality study should therefore report distributions, motion spectra, and net stored energy rather than one best-case voltage.

7. Materials Physics and Transducer Selection

7.1 PZT ceramics

Lead zirconate titanate (PZT) remains a benchmark piezoelectric ceramic because of its high piezoelectric coefficients and electromechanical coupling. Contemporary reviews continue to identify PZT as a high-output material for vibration harvesters (He & Briscoe, 2024; Pan et al., 2024; Radeef et al., 2025). For an in-ear application, however, the relevant question is not whether PZT has a larger coefficient in a datasheet. The question is whether the complete PZT structure can experience useful strain without becoming too stiff, brittle, bulky, or difficult to encapsulate. Lead content also makes robust isolation important when the material could be near skin.

7.2 PVDF and PVDF-based polymers

PVDF has a lower electromechanical response than high-performance PZT in many direct material comparisons, but its low mass, flexibility, thin-film form, and conformability are major system-level advantages for body-coupled devices. Modern PVDF reviews emphasize control of the electroactive β phase, electrospinning, composite strategies, and flexible device architectures for wearable energy harvesting (Zheng et al., 2024). The direct in-ear PVDF demonstration by Delnavaz and Voix (2013b) is particularly important because it shows that flexibility is not merely a packaging convenience; it can allow the active layer to follow the available deformation.

7.3 MEMS and emerging alternatives

MEMS structures can concentrate strain into beams, membranes, or resonators while keeping the active piezoelectric film small. This allows the structural stiffness to be engineered independently from a bulk ceramic plate and can support materials such as thin-film PZT, AlN, or related lead-free systems. The trade-off is greater fabrication and packaging complexity. Recent reviews through 2026 increasingly treat the transducer, mechanical amplifier, interface circuit, and packaging as one co-designed system rather than independent components (Radeef et al., 2025; Ahmad, 2026; Shim et al., 2026).

Table 3. Physics-based comparison of candidate piezoelectric platforms

Criterion	PZT ceramic	PVDF / PVDF-based polymer	MEMS piezoelectric structure
Piezoelectric response	Generally high; strong charge response when effectively strained.	Moderate in many configurations; improved by β -phase control and composites.	Depends on thin-film material and strain-concentrating geometry.
Mechanical compliance	Stiff and brittle.	Flexible, lightweight, conformal.	Engineered via beams/membranes; can be compliant despite stiff film.
Low-frequency body coupling	Requires compliant mounting or amplification.	Naturally suited to bending and distributed deformation.	Often requires frequency conversion, resonance engineering, or nonlinear design.
In-ear packaging	Needs robust isolation and fracture protection.	Favorable for lamination/wrapping and moisture barrier films.	High integration potential but complex microfabrication and encapsulation.
System-level role here	High-output comparison candidate.	Recommended baseline for first physics experiment.	Advanced optimization path after source is measured.

For a first experimental study in a physics department, PVDF is the most defensible baseline because it maximizes the chance that the available ear-canal deformation reaches the active material. PZT should be retained as a controlled comparison, ideally with matched active area and well-defined mechanical boundary conditions. MEMS becomes attractive after the source spectrum and strain map are known well enough to justify a resonant or strain-amplifying microstructure.

8. Proposed System Architecture

The proposed architecture is an energy-recovery chain rather than a replacement power supply. The piezoelectric transducer produces a high-impedance alternating or pulsed output. A low-loss interface must convert this output to a form that can be accumulated, while its own leakage and quiescent current remain below the energy it recovers. Contemporary biomedical reviews emphasize the same

system-level requirement, and 2026 work on miniature biomedical power management further highlights cold start, efficient conversion, storage management, and architecture-level power budgeting (Almarri et al., 2024; Shim et al., 2026).

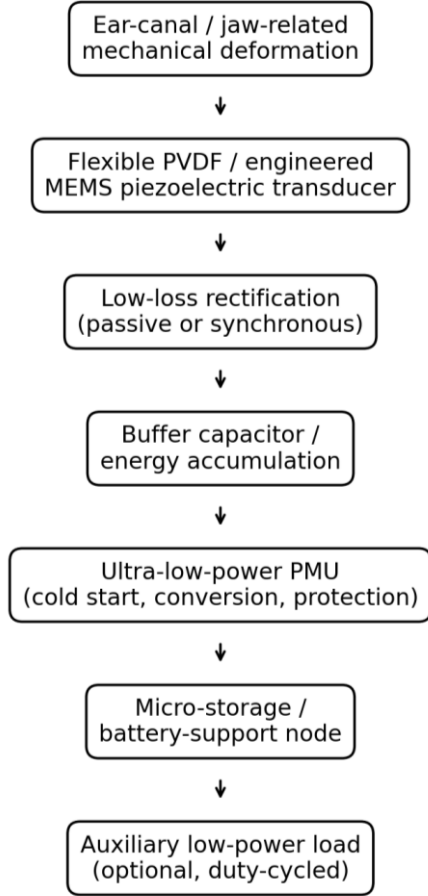


Figure 3. Proposed piezoelectric energy-harvesting architecture for hearing-aid power support. Author's conceptual representation based on the reviewed literature.

8.1 Rectification

A conventional bridge rectifier is simple but imposes two forward-conduction drops during each current path. At a high-impedance, low-energy piezoelectric source, this can remove a large fraction of available voltage. Schottky diodes reduce forward drop but increase reverse leakage. Active synchronous rectifiers can lower conduction loss, while synchronized-switch techniques such as SSHI or charge-extraction approaches can increase harvested energy. Their disadvantage is circuit overhead, startup complexity, and often external inductance. The appropriate topology cannot be selected from voltage alone; it should be selected after measuring source capacitance, waveform, and frequency content (Almarri et al., 2024; Shim et al., 2026).

8.2 Buffering and storage

A buffer capacitor is useful because jaw motion arrives as discrete events. Equation (15) provides a direct way to measure the useful energy accumulated from repeated cycles. For early experiments, capacitor charging is scientifically preferable to direct battery charging because the energy can be calculated transparently from measured voltage and capacitance. A micro-battery or supercapacitor should be introduced only after leakage, voltage range, safety, cycle life, and charging-control requirements are established.

8.3 Ultra-low-power power management

The power-management unit may need cold start, undervoltage lockout, overvoltage protection, DC-DC conversion, impedance adaptation or MPPT, and controlled delivery to storage or an auxiliary load. The best circuit is not the one with the highest efficiency at milliwatt input; it is the one that maintains positive net energy at the actual piezoelectric input level. Quiescent current must therefore be included in every power budget. If the PMU draws 2 μA from a 3 V rail, for example, its 6 μW quiescent consumption would already absorb 10-15% of a hypothetical 40-60 μW harvested output before considering any other loss.

9. Physics-Based Feasibility Assessment

9.1 Required end-to-end efficiency relative to published mechanical source power

A useful feasibility test is to compare the illustrative 40-60 μW electrical target with the 26.2 mW mean mechanical source power reported by Bouchard-Roy et al. (2020) during eating. If those values were applicable to the same user and activity, the required source-to-useful-electric efficiency would be:

$$\eta_{\text{req}} = P_{\text{target}} / P_{\text{mech}} \quad (21)$$

For 40 μW , $\eta_{\text{req}} \approx 0.153\%$; for 60 μW , $\eta_{\text{req}} \approx 0.229\%$. The 70 μW average electrical output reported by Delnavaz and Voix (2013b) corresponds to about 0.267% of 26.2 mW if the numbers are compared only as an order-of-magnitude illustration. This comparison does not establish a true efficiency because the experiments, subjects, mechanical definitions, and activity windows differ. It does, however, show that the desired tens-of-microwatts scale does not violate energy conservation when a milliwatt-scale mechanical source is available. The challenge is achieving that conversion within the hearing-aid constraints.

9.2 Relation to hearing-aid electrical demand

A fully integrated hearing-aid system-on-chip has been reported at 1.1 mW (Chen & Chen, 2019), while complete research hearing-aid platforms with advanced processing

can consume much more depending on architecture and features. Against the 1.1 mW reference alone, 40-60 μW represents about 3.6-5.5% before accounting for downstream losses. This is enough to justify research on battery support, but not enough to justify a universal self-powered claim. The actual benefit should ultimately be expressed in additional operating time per day under a measured activity profile.

9.3 Storage-energy examples

Equation (15) can translate harvested power into a testable storage metric. If 40 μW of net power were continuously delivered to a 100 μF capacitor, raising it from 0 to 3 V requires 0.45 mJ and would take an ideal minimum of 11.25 s. At 60 μW the ideal time would be 7.5 s. For a 1 mF capacitor, the same 0-to-3 V energy is 4.5 mJ, implying 112.5 s at 40 μW or 75 s at 60 μW . Real times would be longer because jaw activity is intermittent and because rectifier, conversion, leakage, and storage losses reduce net power. These examples are engineering calculations, not experimental results.

Table 4. Quantitative interpretation of the 40–60 μW illustrative target

Quantity	40 μW scenario	60 μW scenario	Interpretation
Fraction of 1.1 mW SoC reference	3.64%	5.45%	Supplemental, before added losses.
Required efficiency vs 26.2 mW mechanical source	0.153%	0.229%	Order-of-magnitude only; source study differs.
Ideal time to store 0.45 mJ (100 μF , 0→3 V)	11.25 s	7.50 s	Assumes continuous net power.
Ideal time to store 4.5 mJ (1 mF, 0→3 V)	112.5 s	75.0 s	Real time longer under intermittent motion.

9.4 What the equations establish - and what they do not

The equations establish four points. First, changing ear-canal deformation can generate piezoelectric charge and current without violating energy conservation. Second, source capacitance and excitation frequency create a measurable electrical impedance that must be matched by the interface. Third, the published mechanical source is large enough in principle that a sub-percent recovery efficiency could correspond to tens of microwatts. Fourth, free-field acoustic power over a hearing-aid-sized area is usually too small to support the same claim without strong resonant or structural amplification.

The equations do not prove that a particular hearing aid will deliver 40 or 60 μW . That requires measured force/strain, transducer geometry, capacitance, loaded voltage/current, interface efficiency, leakage, and actual user activity. In other words, the physics supports the concept; the prototype must support the number. This distinction makes the paper stronger, not weaker, because it turns the idea into a falsifiable scientific hypothesis.

10. Contemporary Literature Update (2024–2026)

The recent literature strengthens several parts of the proposed research direction. He and Briscoe (2024) and Pan et al. (2024) summarize advances in material classes, structural design, and the need to consider the entire electromechanical system rather than a piezoelectric coefficient in isolation. Zheng et al. (2024) specifically reviews flexible PVDF-based nanogenerators and emphasizes phase engineering, fibers, and wearable integration. Ali et al. (2024) places human-motion harvesting within a broader wearable-energy framework and reinforces the low-frequency, irregular nature of biomechanical excitation.

For biomedical power systems, Gao et al. (2024) reviews advanced harvesters and storage technologies for wearable and implantable devices, while Almarri et al. (2024) focuses directly on piezoelectric harvesting and ultra-low-power management circuits. Radeef et al. (2025) synthesizes material, configuration, and power-optimization strategies, including the continuing role of MEMS and nonlinear or broadband concepts. The 2026 review by Ahmad discusses commercialization barriers for biomedical and wearable vibration harvesters, highlighting the same issues that matter here: miniaturization, source variability, durability, user compatibility, and realistic system-level power density. Shim et al. (2026) provides a current circuit-level perspective on millimeter-scale biomedical sensing systems and confirms that energy harvesting, conversion, battery management, and storage must be co-designed under severe power constraints.

The application-specific literature is still much smaller than the general wearable literature. Avetissian et al. (2024) is especially valuable because it revisits ear-canal dynamic motion with a new mechanical-transfer architecture. Salemi et al. (2024) provides another recent application-specific contribution: CT-derived ear-canal geometry, measured speaking-related mandibular motion, finite-element simulation, and circuit modeling were combined to estimate piezoelectric output during several speaking activities. Because those reported power conclusions are model-based rather than direct measured net-energy results, they are treated as contemporary feasibility evidence, not as proof of a specific hearing-aid runtime. The small number of direct

in-ear studies remains a research gap: there is room for a carefully instrumented physics study that measures deformation, derives the electromechanical parameters, and reports net stored energy under realistic wearing conditions.

11. Discussion

11.1 Physics supports mechanical harvesting more strongly than acoustic scavenging

The acoustic calculation and the in-ear literature point in the same direction. Ambient sound can produce voltage from a piezoelectric transducer, and studies such as Liew et al. (2017) and Ismail and Loganathan (2024) demonstrate this under controlled sound levels. Yet the incident acoustic power available to a very small area is intrinsically limited. Ear-canal deformation, by contrast, provides direct mechanical work at the boundary of the device. The proposed system should therefore be presented as a biomechanical energy harvester whose source happens to be associated with normal use of an auditory device, not as a device that powers itself from sound.

11.2 Material selection must be based on transferred strain, not datasheet d

PZT can outperform PVDF when both materials experience comparable favorable strain, but an in-ear structure does not guarantee that condition. If a stiff ceramic suppresses the local deformation, a flexible polymer with lower intrinsic coefficient can produce more useful system energy because it experiences a larger strain field. This is why the appropriate optimization variable is energy delivered to storage per motion event, not d_{33} alone. A future experiment should therefore control geometry and boundary conditions when comparing materials.

11.3 The microwatt regime changes circuit design priorities

At microwatt input, conventional power-electronics intuition can fail. Voltage drops, reverse leakage, startup energy, bias currents, and measurement-instrument loading become first-order effects. A circuit with excellent conversion efficiency after startup can still be unsuitable if it requires more startup energy than a realistic jaw-motion sequence provides. The PMU must be characterized from cold start and under intermittent bursts, with all quiescent paths included. This is a central finding of the recent medical power-management literature (Almarri et al., 2024; Shim et al., 2026).

11.4 Renewable-energy interpretation

From the perspective of renewable-energy physics, the proposed device is best classified as micro-scale ambient or biomechanical energy recovery. The harvested energy ultimately originates from human metabolic work and is therefore not a new primary energy source. Its sustainability

value is local: recovering otherwise dissipated energy can reduce the frequency of charging or battery replacement and can support energy-aware electronics. This classification places the application within the broader field of distributed, sustainable energy harvesting without overstating the available energy scale.

11.5 From conceptual feasibility to publishable evidence

A review-based paper can justify the hypothesis, but a stronger journal contribution would require original experimental evidence. The most publishable next step is not simply to show an LED or measure an open-circuit voltage. It is to characterize the source and the entire energy chain. The paper should report ear-canal deformation spectra, mechanical input or proxy variables, transducer capacitance, open-circuit voltage, short-circuit current, loaded power across resistance, rectified energy, PMU efficiency, and final capacitor-energy increase. Repeating the test across users and activities would then allow uncertainty and variability to be quantified.

12. Limitations and Engineering Risks

Table 5. Major limitations, their physical consequences, and required validation

Limitation	Physical / engineering consequence	Required validation
Low and intermittent energy density	Average useful power may be much smaller than peak event power.	Report energy per event and long-duration daily energy, not only peak voltage.
User and activity variability	Source amplitude and frequency change between subjects and behaviors.	Measure multiple users/activities and report distributions.
Rectification and PMU loss	A large fraction of microwatt input can disappear before storage.	Measure end-to-end efficiency from raw piezo output to stored energy.
Leakage	Energy accumulated between jaw events may self-discharge.	Characterize capacitor, battery, PCB, and PMU leakage at operating voltage.
Added stiffness	Harvester can reduce the deformation that creates its energy.	Measure mechanical deformation before/after integration and assess comfort.
Acoustic interference	Added material can block venting, change receiver response, or increase feedback.	Perform electroacoustic frequency-response and feedback tests.

Moisture and cerumen	Electrodes and interconnects can corrode or change impedance.	Perform humidity, sweat/cerumen proxy, and encapsulation tests.
Fatigue	Repeated jaw motion and insertion can crack films or contacts.	Conduct cyclic bending and insertion/removal testing.
PZT safety/packaging	Lead-containing ceramic and brittle fracture require isolation.	Use robust encapsulation or consider lead-free/thin-film alternatives.
No original prototype in this paper	Net power remains unverified for the proposed geometry.	Proceed to controlled prototype validation before stronger performance claims.

13. Experimental Validation Plan and Future Work

1. Source characterization: Measure ear-canal/earpiece deformation during mouth opening, chewing, speech, walking, and quiet wear. Use displacement/strain sensors or optical methods where feasible and extract amplitude and frequency spectra.
2. Matched material comparison: Fabricate a flexible PVDF test coupon and a PZT or MEMS comparison with controlled active area and clearly documented mechanical boundary conditions.
3. Electrical characterization: Measure C_p , open-circuit voltage, short-circuit current, impedance, loaded voltage, and power versus R_L . Verify the approximate matching behavior in Equations (8)–(10).
4. Energy measurement: Rectify the output into a calibrated low-leakage capacitor and use Equation (15) to calculate net stored energy per jaw cycle and per activity window.
5. Interface comparison: Compare passive low-leakage rectification with an ultra-low-power active/synchronous option using the same measured source waveform.
6. Full energy budget: Account for PMU startup energy, quiescent current, leakage, conversion efficiency, and storage self-discharge. Report net—not gross—energy.
7. Acoustic and comfort validation: Confirm that the harvester does not degrade frequency response, venting, seal, feedback stability, comfort, or retention.
8. Environmental reliability: Test humidity, sweat/cerumen exposure, repeated bending, insertion/removal, and long-term mechanical fatigue.
9. Human-subject protocol: If measurements are taken on users, obtain institutional ethical approval and define

safe, non-invasive procedures with inter-subject variability reported.

10. Hybrid harvesting only after baseline: Consider thermal or other hybrid sources only after the mechanical single-source system has a validated energy budget; added complexity should be justified by net energy gain.

14. Conclusion

This study evaluates hearing-aid energy harvesting through the physics of electromechanical conversion and the most relevant modern evidence. The direct piezoelectric constitutive equations show how stress and strain couple to electric displacement; the capacitance and load-matching model show why voltage alone is an inadequate performance metric; mechanical-energy relations show why deformation and frequency content matter; and the acoustic-intensity calculation demonstrates why ordinary free sound over a miniature area is a weak primary source. Published in-ear studies independently establish that jaw-related ear-canal motion contains recoverable mechanical energy and that flexible piezoelectric structures can generate microwatt-scale electrical output under defined conditions.

The most scientifically defensible design therefore uses mechanically coupled ear-canal or jaw-related deformation, a flexible PVDF baseline transducer or carefully engineered MEMS alternative, low-loss rectification, a buffer capacitor, and an ultra-low-power power-management stage. PZT remains important as a high-response comparison material but must be judged at system level because stiffness, brittleness, and packaging can reduce practical strain transfer.

The equations and literature make the concept physically plausible, including the 40-60 μW order of magnitude as a research target in some operating conditions, but they do not prove that a specific hearing aid will achieve that output. The near-term goal should be battery support, gradual energy accumulation, or intermittent auxiliary loads rather than full replacement of the primary battery. A publishable experimental continuation should measure the real mechanical source, the piezoelectric source impedance, rectifier and PMU losses, and the net increase in stored energy under realistic wear conditions. That evidence would convert the present physics-based concept from plausible energy harvesting into a quantitatively validated hearing-aid power-support technology.

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