Electromagnetic Biointeraction and Assistive Communication: Demonstrated Mechanisms, System Architectures, and Evidentiary Limits

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Contents

1 Abstract

Restoring communication for people living with paralysis, anarthria, severe speech impairment, and deafness is among the most consequential goals of contemporary clinical neuroengineering. This white paper synthesizes peer-reviewed literature, governmental and institutional publications, and IEEE sources to establish a rigorous, evidence-hierarchy-first account of how demonstrated assistive communication actually works, and to draw a firm boundary between what the physics and clinical record support and what they do not. The central thesis is answer-first: demonstrated remote and assistive communication is local-sensor, clinical-device, and communications-network engineering. Implanted speech neuroprostheses recover tens of words per minute from *attempted* speech using electrodes on or in the cortex, statistical phoneme decoding, and language-model rescoring [1–3]; cochlear implants and telehealth-programmed hearing devices restore the inbound channel through the peripheral auditory system [4, 5]; and wireless implant links carry digitized samples a few centimeters as *telemetry*, not as a mind-reading radio [1, 6]. We treat the human body accurately as a bounded electromagnetic source, receiver, and coupled dielectric medium governed by quasi-static electrodynamics at neural frequencies [1], never as a general-purpose radio transceiver [7]. We assess claims of satellite-origin or tower/Wi-Fi remote reading or writing of complex thoughts and find no credible mechanistic or empirical support; the one genuine remote RF-to-percept pathway, the microwave auditory (Frey) effect, is peripheral cochlear acoustics, not cortical language injection [8, 9]. We treat "photonic current" precisely: photons are not an electrical current absent a defined charge-separation mechanism, and validated photobiomodulation acts through mitochondrial chromophores, not through satellite neural messaging [10, 11]. We close with governance, exposure-standard, privacy, cybersecurity, and research-agenda findings. This document is educational and scientific analysis, not medical, surgical, or regulatory advice.

Keywords: speech neuroprosthesis; brain-computer interface; volume conduction; specific absorption rate; microwave auditory effect; photobiomodulation; cochlear implant; augmentative and alternative communication; electromagnetic exposure standards; neural data privacy.

2 Executive Findings

The following findings are stated with explicit confidence levels, distinguishing established facts, single-source claims, and projections.

1. **Demonstrated speech restoration is local and statistical.** Published 2023–2025 implanted trials decode attempted speech from electrodes placed on or in speech-motor cortex, mapping cortical features to phoneme probabilities and rescoring with a language model [1–3]. Reported performance ranges from 62 to 78 words per minute, with word error rates as low as single digits on constrained vocabularies [1, 2, 12]. Conversational English runs at roughly 160 words per minute, so these systems remain assistive rather than fully natural [1]. (Established.)

2. **Attempted speech is a stronger signal than inner speech, and inner speech decoding must be command-gated.** The Stanford 2025 work found inner speech

to be a weaker, geometrically related pattern in the same motor areas, decodable in proof of principle and deliberately gated so private rehearsal is not leaked [1]. (Established, single foundational source plus corroborating review [13].)

3. **The body is a bounded EM source and dielectric, not a transceiver.** At EEG and spike-band frequencies, Maxwell's equations reduce to a quasi-static Poisson problem; there is no evidence in the reviewed literature that the human body naturally functions as an antenna or transceiver [1, 7]. (Established.)

4. **The inbound channel is audiology, not microwaves.** If hearing is intact, family speech reaches the patient through the ear; if the ear has failed, cochlear implants and hearing technologies, validated by FDA premarket approval and telehealth studies, are the clinical path [1, 4, 5]. (Established.)

5. **No credible evidence supports satellite-to-brain reading or writing of complex thought.** The only established remote RF-to-percept mechanism, the Frey effect, produces clicks and buzzes via thermoelastic cochlear stimulation, not vocabulary injection into cortex [1, 8, 9]. There is no peer-reviewed evidence for satellite-controlled photonic-current neural messaging [11]. (Established as an absence of evidence.)

6. **Exposure standards protect against substantiated thermal effects.** ICNIRP (2020) and FCC limits are anchored to tissue heating, with the FCC applying a localized SAR limit of 1.6 W/kg averaged over one gram of tissue for portable devices [14, 15]. (Established, with documented scientific dispute over non-thermal effects [16, 17].)

3 Technical Foundations: The Body as a Bounded Electromagnetic System

3.1 Endogenous Bioelectricity and the Quasi-Static Regime

Neurons move ions through membrane channels; those ionic currents in the extracellular space constitute the primary current density that instruments detect [1]. Aligned apical dendrites of cortical pyramidal cells make the cortical sheet behave, at a distance, like a layer of current dipoles standing on the cortical surface—the geometry that makes electroencephalography (EEG) and electrocorticography (ECoG) possible at all [1].

At EEG and spike-band frequencies the displacement current is negligible, induction is negligible, and the full Ampère–Maxwell relation collapses to a Poisson problem. This is the quasi-static approximation of Plonsey and Heppner [1]. The full law,

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}, \tag{1}$$

reduces, when $|\partial \mathbf{D}/\partial t| \ll |\mathbf{J}|$, to current continuity $\nabla \cdot \mathbf{J} \approx 0$ away from primary sources [1]. Here $\mathbf{B}$ is magnetic flux density (tesla), $\mu_0 = 4\pi \times 10^{-7}$ H/m is vacuum permeability, $\mathbf{J}$ is total current density (A/m^2), $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is vacuum permittivity, and $\mathbf{E}$ is

the electric field (V/m), equal to minus the gradient of the scalar potential in this limit [1]. The total current decomposes into an ohmic return term and an impressed neural source,

$$\mathbf{J}(\mathbf{r}) = \sigma(\mathbf{r})\mathbf{E}(\mathbf{r}) + \mathbf{J}_p(\mathbf{r}), \tag{2}$$

where $\sigma(\mathbf{r})$ is tissue conductivity (roughly 0.3 S/m for brain, 0.01 S/m for skull, 0.3 S/m for scalp) and $\mathbf{J}_p$ is the primary current we wish to infer [1]. Substituting yields the forward operator in Poisson form,

$$\nabla \cdot [\sigma(\mathbf{r})\nabla\phi(\mathbf{r})] = \nabla \cdot \mathbf{J}_p(\mathbf{r}), \tag{3}$$

with ϕ the electric scalar potential (volts); EEG measures differences of ϕ [1].

This endogenous bioelectric layer is not merely an epiphenomenon. Transmembrane potentials, maintained by ion channels, pumps, and gap junctions, act as instructive regulatory cues for pattern formation, regeneration, and disease across all cell types, operating in parallel to genetic networks [18–20]. This active bioelectric signaling is conceptually distinct from *volume conduction*—the passive spread of potentials through the conductive medium that governs how localized neural sources are detected at a distance [21, 22]. Both matter here: volume conduction sets the physics of measurement; endogenous signaling explains why the tissue produces measurable fields at all.

3.2 Skull Attenuation and the Limits of Scalp Sensing

The skull is the dominant attenuator and spatial blender of scalp EEG. The skull-to-brain conductivity ratio is on the order of

$$K = \frac{\sigma_{\text{skull}}}{\sigma_{\text{brain}}} \approx \frac{1}{15} \text{ to } \frac{1}{80}, \tag{4}$$

a dimensionless quantity whose exact value varies across published estimates but whose qualitative implication is robust: signals from cortex are heavily smeared before they reach scalp electrodes [1]. This is why interface modalities form a spatial-specificity hierarchy—scalp EEG mixing centimeters, then stereo-EEG depth probes, subdural ECoG grids, and penetrating microelectrode arrays resolving single neurons [1].

A cortical dipole produces microvolts to millivolts at the pial surface and only tens of microvolts at the scalp; in air, off the scalp, there is no ohmic volume conductor to carry the signal, and magnetoencephalography of the same sources measures on the order of 100 femtotesla at a SQUID a few centimeters away [1]. The information-theoretic consequence is decisive. The recoverable message is bounded by mutual information,

$$I(S; N) = H(S) - H(S \mid N), \tag{5}$$

where $H(S)$ is the entropy of the intended message and $H(S \mid N)$ the entropy remaining after observing the neural data N [1]. Unconstrained English inner speech is high-entropy; a 50-word command set is not. For scalp EEG imagined speech, $H(S \mid N)$ remains large; for implanted attempted speech it is driven down [1]. A coil across a room cannot reconstruct inner speech from a 100-femtotesla field [1].

3.3 Dielectric Properties and the Body as Coupled Medium

For externally applied fields, the body behaves as a complex, dispersive dielectric. Tissue permittivity and conductivity are frequency-dependent, organized into four dispersion regions—α (ionic diffusion, 10 Hz–10^3 Hz), β (membrane capacitance and Maxwell–Wagner effects, 10^3–10^7 Hz), γ (dipolar motion of large molecules, 10^7–10^{10} Hz), and δ (water dipole rotation, above 10^{10} Hz) [23, 24]. Above roughly 1 GHz, dielectric behavior is dominated by tissue water content [25]. These properties are precisely why implantable and wearable antennas must contend with signal absorption, frequency detuning from the tissue "loading effect," and miniaturization constraints—and why the body is treated in the engineering literature as a *challenging environment for man-made systems*, not as a natural transceiver [7, 26, 27].

Table 1: Distinct electromagnetic and photonic interaction classes with human tissue

Interaction class	Physical mechanism	Evidence and boundary
Endogenous bioelectricity	Ionic transmembrane currents; quasi-static fields	Established; source of EEG/ECoG/spikes [1, 18]
Externally induced fields/currents	Applied E-field drives ohmic and capacitive currents; nerve stimulation below 10 MHz	Basis of TMS, tES; ICNIRP low-frequency limits [14, 28]
RF heating	Polar-molecule rotation and ion motion dissipate as heat	Only substantiated adverse RF effect per ICNIRP/WHO [29, 30]
Photonic energy deposition	Photon absorption by chromophores (e.g., cytochrome c oxidase)	Photobiomodulation; not an electrical current [10, 11]
Clinically targeted stimulation	Localized field/current or light delivered by a device	Dosed, gated, regulated [31, 32]

4 Evidence Synthesis: Demonstrated Assistive Communication

4.1 From Primary Current to Decoded Speech

ECoG avoids the skull, and high-gamma power on ECoG tracks local firing; it is the workhorse feature of speech decoding [1]. High-gamma bandpower is computed as

$$P_\gamma(t) = \int_{70}^{150} |X(f,t)|^2 \, df, \tag{6}$$

integrated over an empirical band (70–150 Hz) that tracks multiunit firing in human speech cortex, in windows of 10–50 ms [1]. Penetrating arrays record spikes from a few square millimeters of precentral gyrus, which is why BrainGate-style systems achieve high accuracy from a small patch [1]. Ventral sensorimotor cortex is somatotopic for lips,

jaw, tongue, and larynx, with population patterns organized by phonetic features on a tens-of-milliseconds timescale [1].

4.2 The Decoding Stack

Modern systems estimate a distribution over phonemes every few tens of milliseconds, then let a language model repair the sequence [1, 12]. Closed-loop implementations write the problem as a latent state with a linear observation so a Kalman-type filter can run online:

$$z_t = Az_{t-1} + Bu_t + w_t, \qquad y_t = Cz_t + v_t, \tag{7}$$

where z_t is the latent articulatory or embedding state, A the transition matrix, Bu_t the attempted-speech intent drive, w_t process noise, y_t the observed high-gamma or spike features, C a lead-field-like observation matrix, and v_t observation noise [1]. A recurrent backbone summarizes neural history, $h_t = \mathrm{GRU}(x_t, h_{t-1})$, and a softmax yields phoneme posteriors

$$P(c_k \mid x_t) = \frac{\exp(w_k^\top h_t + b_k)}{\sum_j \exp(w_j^\top h_t + b_j)}, \tag{8}$$

with English typically modeled as about 40 phonemes plus silence [1]. Finally a language model rescores:

$$\hat{w}_{1:T} = \arg\max_{w} \left[\sum_t \log P_{\mathrm{nn}}(c_t \mid x) + \alpha \log P_{\mathrm{LM}}(w) \right], \tag{9}$$

where α weighs neural evidence against linguistic plausibility [1]. The transition from traditional classifiers to hybrid CNN/RNN and transformer architectures has been a primary driver of performance gains [33]. Notably, bilingual decoding in a Spanish–English ECoG participant did not require a manual language switch, because the articulatory code is largely shared [1].

4.3 Published Performance

The UCSF team decoded text, synthesized audio, and drove a facial avatar from attempted silent speech with a high-density ECoG grid at a median 78 words per minute and 25 percent large-vocabulary word error rate [1]. Stanford/BrainGate reached 62 words per minute on a 125,000-word vocabulary, later reporting near-ceiling closed-vocabulary accuracy after brief calibration [1]. Independent reviews corroborate this trajectory, reporting conversational word error rates as low as 3.7 percent in some systems and confirming that neural high-gamma signals remain stable over at least 12 months post-implantation [2, 34]. Speech synthesis can now be personalized to a user's pre-injury voice, conveying prosody and emotional nuance [3, 35].

A recognized "validation gap" persists: a systematic review of 115 studies found that although invasive modalities outperform non-invasive ones, only a small fraction validated results in paralyzed individuals, and selection-bias risk is high [33]. Scalp EEG imagined-speech decoding converges on low signal-to-noise ratio, poor spatial resolution, muscle artifact, and tiny public datasets; deep networks help but do not repeal volume conduction [1]. EEG remains a legitimate coarse command channel, not a replacement for implanted systems when the goal is kitchen conversation at tens of words per minute [1].

Table 2: Landmark implanted speech-BCI results, 2023–2025 (conversational English ≈ 160 wpm)

System	Interface and cohort	Headline result
Willett et al., Nature 2023	Intracortical; ALS, attempted speech	62 wpm; 9.1% WER on 50 words; 23.8% WER on 125k words [1, 12]
Metzger et al., Nature 2023	253-channel ECoG; brainstem stroke	78 wpm median; 25% WER; audio plus avatar [1]
Card et al., NEJM 2024	256-site intracortical; ALS dysarthria	99.6% on 50 words after 30 min; 90.2% on 125k words day two [1]
Littlejohn/Chang 2025	ECoG plus vocoder; paralysis trial	Near-synchronous brain-to-voice streaming [1]
Kunz/Willett, Cell 2025	Intracortical; four speech-impaired people	Inner speech weaker; command-gated decoding [1]

4.4 Clinical Need and Indication Boundaries

Loss of intelligible speech after brainstem stroke, ALS, anarthric cerebral palsy, or advanced progressive multiple sclerosis is among the most isolating deficits in neurology [1]. In corticobulbar MS, cortical cell bodies and their local fields may remain while myelin on the descending cable fails—the intent is written in cortex but never reaches muscle, matching the design assumption of the implanted systems [1]. But MS that produces cerebellar dysarthria, cognitive-linguistic impairment, or fluctuating fatigue changes neural features day to day, and the high-rate published systems enrolled brainstem stroke and ALS, not large MS cohorts; extrapolation is biologically reasonable but empirically thin [1]. This is a single-source caution from the foundational volume and should be read as a research gap, not a settled conclusion.

4.5 The Inbound Channel and Assistive Alternatives

For people who retain hearing, inbound communication is solved engineering: talk, use a hearing aid, or use bone conduction when the canal is unusable [1]. When the ear has failed, cochlear implants bypass damaged hair cells: an external microphone and processor code sound into digital signals transmitted by inductive link across the skin to an internal receiver/stimulator, which drives an electrode array in the cochlea to stimulate the auditory nerve [4, 36]. The FDA regulates these as devices requiring premarket approval and clinical evidence of safety and effectiveness, with candidacy defined by pure-tone averages and speech-recognition scores such as CNC word tests [4, 37, 38].

For the broader population unable to use speech, augmentative and alternative communication (AAC) spans no-tech (facial expression, sign), low-tech (communication boards), and high-tech speech-generating devices and eye-gaze systems [39]. Eye-gaze technology uses infrared cameras to track pupil and corneal reflections and select on-screen items, and can significantly enhance quality of life and reduce depression for late-stage ALS

users while helping children with cerebral palsy achieve communication goals [40, 41]. Its success depends heavily on professional and caregiver support [41].

Remote care extends these technologies without extending their physics. Remote cochlear-implant programming yields impedances, neural response telemetry, stimulation levels, and speech-recognition scores statistically equivalent to in-person visits, with one study showing 99 percent concordance for stable aided hearing, reducing travel burden while raising satisfaction [5, 42]. This is teleaudiology—a communications-network overlay on a validated device, not remote sensing of the person.

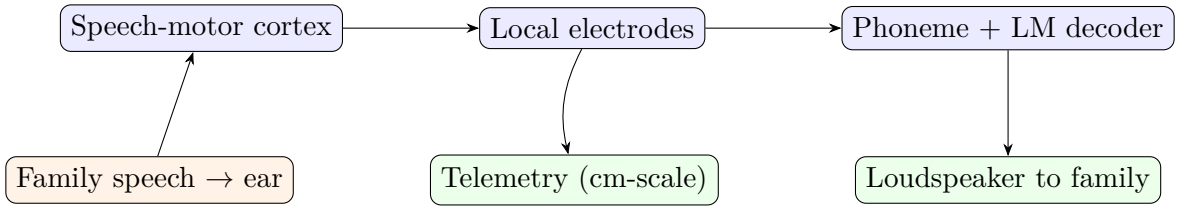

Figure 1: Two-way family architecture matching the physics: intended speech out of motor cortex via local electrodes and a decoder to a loudspeaker; family speech in through the ear (or a cochlear implant). Telemetry is a centimeter-scale data pipe, not remote reading.

5 Validated Modalities: Recording, Stimulation, and Photobiomodulation

5.1 Neural Recording and Wireless Telemetry

A fully implanted wireless speech BCI still has electrodes on cortex; its radio carries digitized samples a few centimeters to a wearable receiver [1]. That is telemetry, not remote mind reading [1]. Wireless neural telemetry denotes in-situ recording by an implanted device that relays data externally—fundamentally different from "remote neural sensing," which would attempt to measure activity from a distance without an implant [43]. Telemetry designs commonly use the Medical Implant Communication Service band (roughly 401–406 MHz) and contend with path loss, tissue attenuation, and tight thermal and power budgets, motivating batteryless, wirelessly powered architectures using magnetic, ultrasonic, or optical links [44–46]. The NIH BRAIN Initiative supported the first human use of a high-bandwidth wireless transmitter—the Brown Wireless Device—delivering single-neuron-resolution data at 48 megabits per second with fidelity comparable to wired systems, enabling home use [6].

5.2 Transcranial Magnetic Stimulation

Transcranial magnetic stimulation (TMS) is externally *induced*, not endogenous. A stimulator discharges current into a coil, creating a rapidly changing magnetic field that penetrates the skull and induces a secondary electric current in tissue, depolarizing or hyperpolarizing neurons [28, 47]. High-frequency ($\geq$5 Hz) stimulation is generally excitatory and low-frequency ($\leq$1 Hz) inhibitory; dose is calibrated to a motor threshold [47,

48]. The FDA regulates repetitive TMS systems as Class II devices with special controls, cleared for major depressive disorder, obsessive-compulsive disorder, smoking cessation, and migraine, with seizure risk mitigated by pulse-train limits [31, 48]. Metallic or ferromagnetic head/neck implants—including cochlear implants—are strict contraindications [49, 50].

5.3 Transcranial Electrical Stimulation

Transcranial electrical stimulation (tES) applies weak scalp currents (typically $\leq$2 mA); resulting brain electric fields are often below 1 V/m [32]. tDCS modulates excitability via sustained depolarization or hyperpolarization; tACS entrains endogenous oscillations [51, 52]. Spatial targeting is imperfect: peak fields often occur at electrode edges, cortical folding produces speckled distributions, and deep structures receive only diffuse stimulation [32, 53]. High-definition montages improve focality [54]. Researchers caution against attributing behavioral effects solely to the region beneath an electrode because of peripheral co-stimulation [32].

5.4 Photobiomodulation and the Precise Meaning of "Photonic Current"

Photobiomodulation (PBM) uses red to near-infrared light (roughly 600–1100 nm) whose photons are absorbed by mitochondrial cytochrome c oxidase, dissociating inhibitory nitric oxide, restoring electron transport, and increasing ATP synthesis [10, 55]. This is photon *energy deposition* into a chromophore—not an electrical current. Photons do not constitute an electrical current absent a defined conversion or charge-separation mechanism (photoconductive or photoelectric); PBM instead triggers biochemical cascades [10]. Transcranial PBM faces severe attenuation through scalp and skull and lacks dosimetry consensus, following a biphasic Arndt–Schultz dose response [10]. This distinction is essential to the satellite assessment below: invoking "photonic current" as a remote neural-writing mechanism conflates optical energy deposition with charge transport, and no validated pathway links the two at a distance [11].

6 The Microwave Auditory (Frey) Effect: The One Real Remote RF-to-Percept Pathway

Pulsed radiofrequency energy can be heard as clicks—the Frey effect [1, 8]. When short, high-peak-power microwave pulses are absorbed in head soft tissue, they induce a rapid, minuscule temperature rise of order 10^{-5} K per pulse; thermoelastic expansion launches an acoustic pressure wave that travels by bone conduction to the cochlea and stimulates auditory receptors as ordinary bone-conducted sound [1, 8, 9]. The governing quantities are specific absorption rate,

$$\mathrm{SAR} = \frac{\sigma |\mathbf{E}|^2}{\rho} \quad [\mathrm{W/kg}], \tag{10}$$

with σ the RF conductivity, $|\mathbf{E}|$ the rms field in tissue, and ρ mass density; and the thermoelastic wave equation

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\beta}{\kappa}\frac{\partial^2 T}{\partial t^2}, \tag{11}$$

where p is acoustic pressure, $c \approx 1500$ m/s in soft tissue, β the thermal expansion coefficient, κ a thermal capacity factor, and T temperature; a temperature acceleration sources pressure [1]. The Frey threshold transient is $\Delta T_{\text{th}} \approx 10^{-5}$ K, illustrating that this is cochlear acoustics, not cortical language injection [1].

Critically, destroying the cochlea eliminates the response in animal models, confirming a peripheral, not central, mechanism [56]. The effect requires pulsed or modulated energy; continuous-wave radiation does not produce it [56, 57]. Frequencies from roughly 200 MHz to 3 GHz have been reported effective, and the percept can be masked by ambient noise [8, 58]. ICNIRP removed the microwave-hearing restriction from its 2020 guidelines precisely because it is a sensory phenomenon rather than an adverse health effect [59]. While the effect has been proposed as a hypothesis for "Havana syndrome," experts including Kenneth Foster argue the observed health effects do not align with its known physics, and there is no verified evidence of its use in directed-energy attacks [8, 9]. It does not support transmission of complex thoughts or behavioral control [8, 60].

7 Assessment of Satellite-Origin Electromagnetic and Optical Claims

7.1 Link-Budget and Coupling Constraints

Any claim that a satellite could remotely read or write complex thought must survive three independent physical constraints, each of which the reviewed evidence renders fatal.

First, **the read direction fails on signal magnitude and volume conduction.** Endogenous neural fields are microvolts at the pial surface, tens of microvolts at the scalp, and about 100 fT magnetically a few centimeters away; there is no ohmic conductor in air to carry them, so even a coil across a room cannot reconstruct inner speech, let alone a platform in orbit [1]. The mutual-information bound formalizes that unconstrained inner speech is high-entropy and that scalp-level observation leaves $H(S \mid N)$ large [1].

Second, **the write direction via RF fails on the heating constraint.** Satellite uplink signals are highly directional—often compared to a flashlight beam—and the FCC restricts public access where exposure could approach limits [61]. To deposit enough energy for any nonthermal "writing," one would first exceed SAR-based thermal limits: the FCC portable-device limit is 1.6 W/kg averaged over one gram, and ICNIRP/IEEE historically use 2.0 W/kg over ten grams [15, 62]. The only established RF-to-percept path, the Frey effect, is peripheral cochlear clicking, and achieving intelligible "voice" would require power levels likely to cause thermal injury first [8, 9].

Third, **the optical/"photonic current" direction fails on penetration and mechanism.** Passive optical remote sensing relies on reflected or emitted radiation and interacts with surfaces [63]. Even clinical transcranial PBM struggles to penetrate scalp and skull

[10]. Photons deposited in tissue are not an electrical current absent charge separation [10]. There is no peer-reviewed evidence that satellite technology can communicate with or control the brain via photonic currents; the term "photonic currents" in the legitimate literature refers to light-based information processing within biological structures or integrated chips, not long-distance brain manipulation [11].

7.2 Biophotons and Photonic BCIs Do Not Bridge to Satellites

Living tissue does emit ultraweak photon emission (biophotons, roughly 200–800 nm) tied to reactive-oxygen-species metabolism, at intensities of a few to several hundred photons per second per square centimeter—invisible without photomultiplier tubes [11]. Proposed "photonic" BCIs envision chips on the interior skull surface to extract features from these signals for diagnostics, not to receive external commands [11]. So-called "mind-controlled" metasurfaces are entirely terrestrial, tuning electromagnetic surfaces from local EEG [11]. The scientific community explicitly emphasizes epistemic restraint and mechanistic specificity: electromagnetic and photonic phenomena in the brain are measurable, but their functional role in high-level neural computation remains under investigation, not established fact [11]. DARPA's completed N3 program, which pursued nonsurgical read/write interfaces, defined its own goal as interacting with a 16 mm^3 volume through 16 channels using wearable or minutely invasive hardware placed on or in the head—explicitly acknowledging that signals through skin, skull, and brain scatter and attenuate severely [64, 65]. Even this well-funded program presumed local hardware, not remote satellite coupling.

7.3 Environmental versus Laboratory and Space Exposures

It is essential to distinguish exposure regimes. Terrestrial satellite-link and tower RF exposure at ground level is far below guideline limits and, per WHO, base-station exposures in public areas are typically thousands of times below international standards [66]. This is categorically different from the high-LET galactic cosmic radiation and solar particle events astronauts face beyond low Earth orbit, which cause clustered DNA damage and are studied by NASA as carcinogenesis, CNS, degenerative, and acute-syndrome risks [67–69]. Space radiation is ionizing and biologically potent; terrestrial RF is non-ionizing, with photons far too weak to break chemical bonds [70, 71]. Conflating the two—treating a satellite communications link as if it delivered space-radiation-like biological potency to a person on the ground—is physically unfounded.

8 Electromagnetic Interaction of Networks with Tissue: Standards and Disagreements

8.1 The Exposure-Standard Framework

ICNIRP's 2020 guidelines cover 100 kHz to 300 GHz and are anchored to the single substantiated adverse effect: tissue heating [14, 29]. Basic restrictions are internal quantities—SAR (W/kg) below 6 GHz, absorbed power density (W/m^2) above—while

Table 3: Mechanism claims versus evidence strength for remote biological interaction

Claimed mechanism	Evidence status	Basis
Local electrode speech decoding	Established	Trials, reviews [1, 2]
Cochlear implant inbound hearing	Established	PMA, clinical [4, 37]
Wireless implant telemetry (cm-scale)	Established	Devices, IEEE [6, 46]
Frey effect (RF clicks via cochlea)	Established, peripheral only	Frey; Lin & Wang [8, 9]
Non-thermal RF health effects (population)	Disputed, not substantiated	ICNIRP/WHO vs. ICBE-EMF [16, 29]
Satellite reading of complex thought	No credible evidence	Physics, mutual-info bound [1, 7]
Satellite "photonic-current" neural writing	No peer-reviewed evidence	Biophotonics reviews [11]

reference levels are measurable external field strengths chosen so compliance with either ensures safety [14, 59]. Conservative reduction factors account for biological variability; the fetus is treated as a member of the general public [59]. Between 100 kHz and 10 MHz, guidelines also limit induced fields that could stimulate nerve and muscle [14]. Low-frequency limits target peripheral nerve stimulation as the critical constraint, with active debate over whether peak-based rather than RMS metrics better match all-or-nothing action-potential thresholds [72, 73]. The FCC uses SAR (1.6 W/kg over one gram) for portable devices and Maximum Permissible Exposure for fixed transmitters, with OET Bulletin 65 as the compliance reference [15, 74].

8.2 Where the Evidence Conflicts

Two positions must be presented honestly. The dominant institutional position—ICNIRP, WHO, FCC, FDA—holds that no consistent, reproducible adverse health effect has been demonstrated below the thermal threshold, across roughly 25,000 articles reviewed over 30 years [29, 30]. WHO notes that electromagnetic-hypersensitivity symptoms are not reproduced under blinded exposure, consistent with a nocebo effect [75, 76]. The dissenting position, advanced by ICBE-EMF and others, argues the thermal-only 4 W/kg threshold rests on 1980s behavioral studies in small animal groups and ignores non-thermal effects; a 2021 D.C. Circuit remand faulted the FCC for not adequately addressing record evidence on non-cancer effects [16, 77]. On animal carcinogenicity the evidence is itself contested: some systematic reviews assign high certainty to heart schwannoma and moderate to brain glioma in male rats from NTP-type data, while 2026 re-analyses applying meta-analysis and dose-response modeling lower that certainty, and human epidemiology (including INTEROCC) finds no consistent association [17, 78, 79]. On balance, the better-supported conclusion for present environmental exposures is the institutional one; the dissent is best read as a call for improved chronic-exposure and dose-response research rather than as an established demonstration of harm.

9 Risk, Ethics, Governance, and Cybersecurity

9.1 Privacy and Command Gating

Inner speech is not public speech; an always-on decoder would convert private rehearsal into an audible sentence, so command-gating, on-device processing, and a physical mute are required ethics, not accessories [1]. This design directly matches the 2025 finding that inner speech is weaker and decodable [1]. Neurodata reveals identity, neurological health, and cognitive states, warranting granular controls, hard on/off switches, encryption at rest and in transit, and privacy-preserving computation such as homomorphic encryption and differential privacy [80, 81]. Legislative "neurorights" initiatives and standards such as IEEE 2857 aim to formalize protection [80].

9.2 Cybersecurity of Implanted and Wearable Systems

Wireless telemetry is a primary attack vector: eavesdropping, injection and replay of therapy commands, denial-of-service battery depletion, and exploitation of unauthenticated magnetic switches [46, 82]. Neural-interface risks span data (privacy leakage), permission (identity/authentication), and model (adversarial manipulation of decoders) levels [83]. The FDA now treats cybersecurity as integral to safety, requiring under FD&C Act Section 524B a Secure Product Development Framework, Software Bill of Materials, vulnerability-management and incident-response plans, and penetration testing for "cyber devices" [84, 85]. IEEE/UL 2933 offers the TIPPSS framework (trust, identity, privacy, protection, safety, security) for clinical IoT [86].

9.3 Clinical Translation and Governance

Published US speech neuroprostheses proceed under FDA investigational device exemptions and IRB oversight (for example, BrainGate NCT00912041); that path, not a consumer-headset claim, is how a family-facing implant becomes legal hardware [1]. The FDA regulates implanted BCIs via 2021 "leapfrog" guidance, typically as high-risk Class III devices requiring an IDE then PMA, with enhanced software documentation and rigorous non-clinical testing including electromagnetic compatibility and wireless coexistence [87, 88]. A 2024 FDA–NIH workshop stressed the absence of consensus clinical outcome assessments needed for pivotal-trial design and reimbursement [89]. IRBs struggle to source neurosurgical and cybersecurity expertise, and premarket-focused frameworks under-address long-term post-market surveillance of devices that may induce lasting neural change [88, 90]. Family-facing design should formalize caregivers as partners in ongoing, transparent consent and long-term device support, since participants have previously lost devices when trial funding ended [91, 92].

10 Bounded Conclusions

The electrodynamics of cortex and the clinical record jointly support a narrow, powerful conclusion. Demonstrated assistive communication for paralysis, anarthria, severe speech

impairment, and deafness is achieved by placing sensors on or in the body, decoding local signals statistically, delivering output through loudspeakers or the peripheral auditory system, and moving data across ordinary communications networks under regulatory oversight [1, 4, 6]. The body is a bounded electromagnetic source and a coupled dielectric medium, well described by quasi-static physics at neural frequencies and by dielectric dispersion for applied fields, but it is not a general-purpose radio transceiver [1, 7, 23]. The single genuine remote RF-to-percept pathway, the Frey effect, produces cochlear clicks by thermoelastic transduction and cannot inject vocabulary into cortex [8, 9]. "Photonic current" is not a real neural-writing mechanism absent charge separation, and there is no peer-reviewed evidence for satellite-to-person neural messaging [10, 11]. Exposure standards protect against substantiated thermal effects, with a documented and unresolved scientific debate over chronic non-thermal exposure that motivates further research rather than alarm [16, 29]. These conclusions are constrained by the current evidence base: high-rate speech systems rest on a handful of landmark patients per year, indication coverage (notably MS heterogeneity) is thin, and long-term stability and post-market governance remain open [1, 33].

11 Research Agenda

1. **Close the validation gap.** Prioritize larger controlled trials that validate invasive and non-invasive decoders in paralyzed populations and reduce selection bias [33].

2. **Characterize indication heterogeneity.** Design trials that measure MS and other heterogeneous cohorts directly rather than assuming extrapolation from stroke and ALS [1].

3. **Develop consensus clinical outcome assessments** tied to how patients feel and function, to support pivotal-trial design and reimbursement [89].

4. **Advance day-to-day stability, fully implanted packages, and premorbid-voice vocoders** while maintaining mandatory command gating for inner speech [1, 35].

5. **Improve exposure science** through rigorous chronic-exposure, dose-response, and consistent meta-analytic methods to resolve the non-thermal debate [78, 93].

6. **Standardize security and privacy engineering** across telemetry, software, and sensor interfaces under frameworks such as the FDA SPDF and IEEE/UL 2933 TIPPSS [85, 86].

7. **Formalize caregiver and post-trial support** so that family-facing devices remain available and consent remains ongoing beyond the trial window [91, 92].

This document is an educational and scientific analysis. It is not medical, surgical, or regulatory advice. Clinical decisions belong to a qualified clinician, a trial team, and the person who would use the device [1].

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