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Ethical aspects of invasive neurotechnologies: an integrative literature review

Ricardo Ferreira Gomes [1], *Rejane Laranja* [1], *Jonas Byk* [1], *Silvania Furtado* [1], *Robson Amorim* [1]

1. Universidade Federal do Amazonas, Manaus/AM, Brasil.

Abstract

Advances in neurotechnologies, such as deep brain stimulation and brain-computer interfaces, have expanded therapeutic and cognitive possibilities, but have also generated unprecedented ethical dilemmas. This study conducted an integrative literature review based on PRISMA guidelines using Medline, Lilacs, BVS, and SciELO databases, including 23 articles published between 2015 and 2025. The analysis identified five main ethical axes: autonomy and informed consent; identity and authenticity; mental privacy and fundamental neurorights; justice and equitable access; and moral responsibility and governance. The results indicate that neurotechnologies challenge the classical principles of bioethics and require new forms of global ethical governance capable of protecting cognitive freedom, mental dignity, and equity of access. It is concluded that contemporary bioethics must anticipate risks and propose guidelines that reconcile technological innovation with the safeguarding of the human condition.

Keywords: Bioethics. Informed Consent. Deep brain stimulation. Brain-computer interfaces. Privacy. Biomedical technology. Human rights.

Resumo

Aspectos éticos das neurotecnologias invasivas: revisão integrativa da literatura

O avanço das neurotecnologias, como estimulação cerebral profunda e as interfaces cérebro-computador, tem ampliado as possibilidades terapêuticas e cognitivas, mas também provocado dilemas éticos inéditos. Este estudo realizou revisão integrativa da literatura, com base nas diretrizes PRISMA, nas bases Medline, Lilacs, BVS e SciELO, de 23 artigos publicados entre 2015 e 2025. A análise evidenciou cinco eixos éticos principais: autonomia e consentimento informado; identidade e autenticidade; privacidade mental e direitos neurais fundamentais; justiça e acesso equitativo; e responsabilidade moral e governança. Os resultados apontam que as neurotecnologias desafiam os princípios clássicos da bioética e demandam novas formas de governança ética global, capazes de proteger a liberdade cognitiva, a dignidade mental e a equidade no acesso. Conclui-se que a bioética contemporânea deve antecipar riscos e propor diretrizes que conciliem inovação tecnológica e salvaguarda da condição humana.

Palavras-chave: Bioética. Consentimento livre e esclarecido. Estimulação encefálica profunda. Interfaces cérebro-computador. Privacidade. Tecnologia biomédica. Direitos humanos.

Resumen

Aspectos éticos de las neurotecnologías invasivas: revisión integradora de la literatura

El avance de las neurotecnologías, como la estimulación cerebral profunda y las interfaces cerebro-computadora, ha ampliado las posibilidades terapéuticas y cognitivas, pero también ha generado dilemas éticos sin precedentes. Este estudio realizó una revisión integradora de la literatura, basada en las directrices PRISMA, en las bases Medline, Lilacs, BVS y SciELO, incluyendo 23 artículos publicados entre 2015 y 2025. El análisis evidenció cinco ejes éticos principales: autonomía y consentimiento informado; identidad y autenticidad; privacidad mental y derechos neurales fundamentales; justicia y acceso equitativo; y responsabilidad moral y gobernanza. Los resultados indican que las neurotecnologías desafían los principios clásicos de la bioética y exigen nuevas formas de gobernanza ética global capaces de proteger la libertad cognitiva, la dignidad mental y la equidad en el acceso. Se concluye que la bioética contemporánea debe anticipar riesgos y proponer directrices que concilien la innovación tecnológica con la salvaguarda de la condición humana.

Palabras clave: Bioética. Consentimiento informado. Estimulación encefálica profunda. Interfaces cerebro-computador. Privacidad. Tecnología biomédica. Derechos humanos.

Research

The authors declare no conflict of interest.

Neurosurgical interventions have evolved notably since the first brain stimulation techniques in the 1950s and 1960s, culminating in high-precision procedures such as deep brain stimulation (DBS) and brain-computer interfaces (BCI). These advances enable direct intervention in neural activity to restore motor functions, treat psychiatric disorders, and, more recently, enhance human cognitive and communicative capacities [1].

Historically, functional neurosurgery has been guided by biomedical principles based on the proportionality between risks and benefits. However, the rise of devices capable of reading and modulating mental states has redefined the boundaries between cognitive therapy and manipulation, shifting the ethical debate to philosophical and legal dimensions of subjectivity [2].

BCIs and DBS are ushering in a new frontier in human-machine integration, in which the brain simultaneously becomes the source and destination of neural data. This symbiosis challenges classical notions of identity and agency, as brain modulation systems can affect the autonomy and continuity of the self [1,3].

While BCIs decode neural signals to enable communication or control of devices, DBS modulates specific circuits and shows proven efficacy in disorders such as Parkinson's, treatment-resistant depression, and obsessive-compulsive disorder (OCD). However, both pose ethical dilemmas concerning consent and personal authenticity [4,5].

Contemporary bioethics shifts its focus from mere physical safety to the protection of subjectivity and mental integrity, giving rise to the concept of fundamental neural rights (neurorights)—a set of rights for safeguarding cognitive freedom, neural privacy, and personal identity [6-8].

The growing participation of private companies has intensified the risks of neural data exploitation and mental manipulation. The commercialization of these technologies requires new governance and transparency models, especially in the face of algorithmic opacity and the possibility of external control of brain implants (brainjacking) [9,10].

Considering this scenario, traditional informed consent proves insufficient. Adaptive technologies and autonomous learning systems require continuous and revisable consent, recognizing the vulnerability of the neurotechnological subject [11,12].

Internationally, organizations such as the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the Institute of Electrical and Electronics Engineers (IEEE) propose guidelines for brain data governance and mental rights protection [13]. Still, there is a persistent gap between technological advancement and ethical regulation.

Understanding how the contemporary bioethical literature addresses ethical conflicts related to autonomy, personal identity, and neural privacy is essential for outlining a new ethical paradigm for neurosurgery in the 21st century.

Method

This is an integrative literature review, conducted in six stages: identification of the theme and formulation of the guiding question, definition of inclusion and exclusion criteria, search in databases, selection of studies, extraction and categorization of information, and synthesis of results [14]. The research was guided by the following question: "What are the main ethical aspects related to the use of invasive neurotechnologies described in the contemporary scientific literature?" As secondary issues, the study sought to identify the most frequently discussed ethical dilemmas, the bioethical principles under consideration, and the ethical governance proposals presented in the literature.

The research was conducted in the MEDLINE (PubMed), Lilacs, BVS, and SciELO databases, with controlled and uncontrolled descriptors related to neurotechnology, neuroethics, brain-computer interfaces, neuromodulation, and deep brain stimulation, combined by the Boolean operators "AND" and "OR."

We included scientific articles published in the last ten years, available in full text, in English, Portuguese, or Spanish, that addressed ethical, social, legal, or philosophical aspects related to neurotechnologies. We excluded duplicate studies, articles not directly related to the issue, editorials, letters to the editor, theses, and dissertations.

Chart 1. Research search strategies

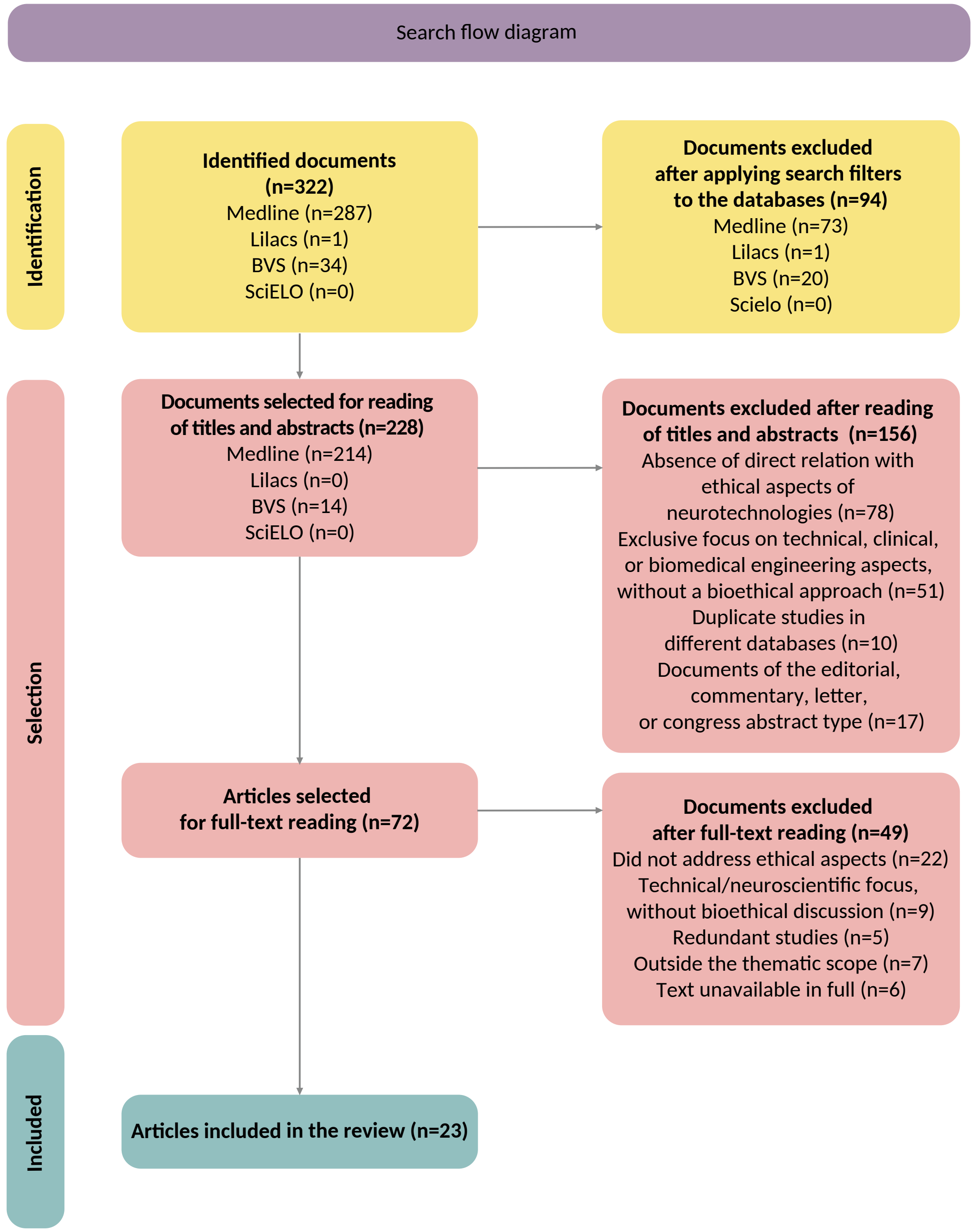
Database	Keywords used
PubMed/MEDLINE	(“deep brain stimulation”[tiab] OR DBS[tiab] OR “brain-computer interface”[tiab] OR “brain computer interface”[tiab] OR BCI[tiab] OR “invasive neurotechnology”[tiab] OR “neuroprosthesis”[tiab] OR “neural implant”[tiab] OR neuromodulation[tiab]) AND (neuroethics[tiab] OR “neuroethics”[tiab] OR bioethics[tiab] OR ethics[tiab] OR ethical[tiab] OR moral[tiab]) AND (“personal identity”[tiab] OR identity[tiab] OR personality[tiab] OR self[tiab] OR selfhood[tiab] OR agency[tiab] OR personhood[tiab] OR “neural privacy”[tiab] OR “mental privacy”[tiab] OR privacy[tiab] OR “brain data”[tiab] OR neurorights[tiab] OR “cognitive liberty”[tiab] OR “mental integrity”[tiab] OR “informed consent”[tiab] OR consent[tiab])
Lilacs	(“estimulação cerebral profunda” OR DBS) AND (bioética OR “ética médica”)
BVS	(“estimulação cerebral profunda” OR DBS) AND (bioética OR “ética médica”)
SciELO	(“deep brain stimulation” OR “estimulação cerebral profunda” OR DBS OR “brain-computer interface” OR BCI) AND (bioética OR ética)

The study identification and selection process followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [15]. The systematic search in the databases initially resulted in 322 records: 287 in MEDLINE, 1 in Lilacs, 34 in BVS, and none in SciELO. After applying search filters, 94 records were excluded, leaving 228 articles for reading of titles and abstracts. Subsequently, after duplicate exclusion, screening, and full-text reading, we included 23 articles that met the established eligibility criteria. The selection process is described in the PRISMA flow diagram (Figure 1).

During the screening, 156 records were excluded for not having a direct ethical relation, for presenting a technical/biomedical focus, duplication, or non-scientific format (editorials and commentaries). After full-text reading of the remaining texts (n=72), 49 studies were excluded due to lack of substantive ethical approach, technical focus, redundancy, text unavailability, or thematic divergence.

At the end of the process, 23 articles met the eligibility criteria and were included in the review. The extracted data were organized into a proprietary spreadsheet containing author, year, title, objective, study type, journal, and main results. Data analysis followed the content analysis technique, comprising the stages of pre-analysis, exploration of the material, and treatment of results, with the identification of convergent thematic categories.

Figure 1. Search flow diagram



Source: adapted from PRISMA Flow Diagram [16]

Results

The analyzed studies were published in the last ten years, with a predominance in the last five years, which shows the recent growth in ethical discussions about neurotechnologies. Most publications were retrieved from international journals in the fields of neuroscience, bioethics, and social sciences applied to technology, with notable contributions from Europe and North America, followed by publications from Asia and Latin America.

There was predominance of theoretical essays and narrative reviews, followed by qualitative empirical research involving specialists or users of neural technologies. The thematic scope comprised deep brain stimulation, brain-computer interfaces, adaptive technologies, and intelligent neuroprosthetics, reflecting the diversity of clinical and experimental applications.

Integrative analysis enabled the identification of five central ethical categories, which outline the contemporary landscape of bioethical concerns on the use of neurotechnologies.

Chart 2. Analysis material

Autoria; ano	Study title	Main results
Goering S, Brown T, Klein E; 2021 [1]	Neurotechnology ethics and relational agency	Proposes the concept of "coagency" and relational ethics.
Kostick-Quenet K and collaborators; 2022 [5]	Researchers' ethical concerns about using adaptive deep brain stimulation for enhancement	Identifies ethical concerns with safety, justice, and naturalness.
Wind JJ, Anderson DE; 2008 [17]	From prefrontal leukotomy to deep brain stimulation: the historical transformation of psychosurgery and the emergence of neuroethics	Analyzes the transition from classical psychosurgery to contemporary techniques (DBS and VNS), noting the role of neuroethics in redefining ethical boundaries in invasive psychiatric treatment.
Bell E, Mathieu G, Racine E; 2009 [18]	Preparing the ethical future of deep brain stimulation	Dilemmas on patient selection, informed consent, and equity; notes the amplification of ethical challenges in new applications.
Clausen J; 2011 [19]	Conceptual and ethical issues with brain-hardware interfaces	Identifies dilemmas on identity, consent, and neural privacy.
Racine E, Bell E, Zizzo N; 2015 [20]	Deep brain stimulation: a principled and pragmatic approach to understanding the ethical and clinical challenges of an evolving technology	Proposes a pragmatic approach to contextualize ethical principles in clinical practice; notes dilemmas of consent, equity, and risks.
Halpern C; 2016 [21]	A commentary on attitudes towards deep brain stimulation for addiction	Identifies ethical risks in the application of DBS in vulnerable populations; questions the validity of consent under additive compulsion; discusses dilemmas of financial incentives and changes in identity and morality.
Viaña JNM, Bittlinger M, Gilbert F; 2017 [22]	Ethical considerations for deep brain stimulation trials in patients with early-onset alzheimer's disease	Identifies ethical dilemmas on selection, genetic consent, and communication of results.
Witt K; 2017 [23]	Identity change and informed consent	Criticizes the traditional consent model and proposes the "perspective-sensitive approach."
Siegel AM, Barrett MS, Bhati MT; 2017 [24]	Deep brain stimulation for Alzheimer's disease: ethical challenges for clinical research	Risks of consent and therapeutic illusion; proposes an ethical decisional algorithm.
Zuk P and collaborators; 2018 [25]	Neuroethics of neuromodulation: an update	Identifies nine ethical axes: neural privacy, consent, device access, DIY *neurostimulation*, *neuroenhancement*, media, identity, agency, and use in minors.

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Chart 2. Continuation

Autoria; ano	Study title	Main results
Zuk P, Lázaro-Muñoz G; 2021 [26]	DBS and autonomy: clarifying the role of theoretical neuroethics	Distinguishes moral, decisional, and executive autonomy; proposes a conceptual methodology to ground empirical measures; advocates for integration between theoretical ethics and neuroscience.
Mandarelli G and collaborators; 2018 [27]	Informed consent decision-making in deep brain stimulation	Cognitive and emotional impairments can compromise the capacity for consent.
Kreitmair KV; 2019 [28]	Dimensions of ethical direct-to-consumer neurotechnologies	Defines seven core ethical dimensions: safety, privacy, authenticity, transparency, justice, etc.
Cannard C and collaborators.; 2020 [29]	Self-health monitoring and wearable neurotechnologies	Presents advances in wearable EEG and discusses ethical challenges in privacy and consent.
Klein E; 2020 [30]	Ethics and the emergence of brain-computer interface medicine	Highlights new clinical responsibilities and ethical concepts such as neural privacy and authenticity.
Van Stuijvenberg OC and collaborators; 2024 [31]	Developer perspectives on the ethics of AI-driven neural implants: a qualitative study	Identifies three ethical axes: *design*, clinical trials, and social impacts; highlights tensions between accuracy and autonomy.
Ruiz S and collaborators; 2024 [32]	Neurorights in the constitution: from neurotechnology to ethics and politics	Identifies conceptual ambiguity and risks of overregulation that may restrict neuroscience research.
Bluhm R and collaborators; 2024 [33]	Stakeholders' ethical concerns regarding psychiatric electroceutical interventions: results from a US nationwide survey	DBS and ABI raise major ethical concerns, especially on consent and efficacy.
Livanis E and collaborators; 2024 [34]	Understanding the ethical issues of Brain-Computer Interfaces (BCIs)	Identifies dilemmas on dignity, autonomy, privacy, and justice.
Moumdjian RA; 2025 [35]	Bioethics of neurotechnologies	Security, justice, privacy, and risk issues.
Zhang Q and collaborators; 2025 [36]	Ethical governance of clinical research on the brain-computer interface for mental disorders: a modified Delphi study	Emphasis on autonomy, privacy, and risk-benefit ratio.
Shaw J and collaborators; 2025 [37]	Current neuroethical perspectives on deep brain stimulation and neuromodulation for neuropsychiatric disorders: a scoping review of the past 10 years	Focus on autonomy, identity, and justice.

Autonomy and informed consent

Most studies noted the challenges in ensuring informed consent in studies and interventions with invasive devices, especially in situations of cognitive impairment or psychiatric disorders. Patient autonomy is considered as to the asymmetry of information between participants and researchers, as well as by the technical complexity of the devices, which requires specific strategies for communication and longitudinal follow-up.

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Identity, authenticity, and personal agency

Several studies addressed the effects of neurotechnologies on self-perception and the sense of personal continuity. Brain stimulation-associated personality, behavior, or mood changes raise questions about the authenticity of subjective experience and the attribution of moral responsibility. Part of the recent literature proposes relational agency models (personal agency), understood as the individual capacity to act autonomously and in a morally significant manner. From this perspective, the idea of shared agency is discussed, considering the user-device interaction as a means of action co-authorship.

Mental privacy and neurorights

With the advancement of brain-computer interfaces and artificial intelligence applied to neural monitoring, there arise concerns on the privacy of brain data and the possibility of decoding thoughts or emotions. Various authors propose the consolidation of fundamental neurorights such as cognitive freedom, mental integrity, and psychological continuity as legal instruments for protection against the manipulation of neural data.

Justice, access, and technological governance

Discussions on distributive justice and equitable access were recurrent. Neural technologies, with high cost and restricted access, tend to reproduce socioeconomic inequalities, both between countries and within healthcare systems. The literature recommends the development of public policies and international regulatory frameworks that promote transparency, inclusion, and ethical regulation of the clinical and experimental use of neurotechnologies.

Ethical responsibility and governance

This category covers concerns about moral and legal responsibility in actions mediated by neurotechnological devices. Issues regarding authorship of actions, technical failures, and responsibility shared among patient, professional, and manufacturer were widely discussed. Studies noted the need for multidisciplinary committees and continuous ethical governance protocols to mitigate risks and ensure safety, traceability, and accountability.

Studies show a rapidly expanding field that associates technological innovation with ethical dilemmas that are complex and still insufficiently regulated. There is consensus on the urgency of integrated international guidelines, capable of harmonizing the principles of bioethics—autonomy, beneficence, justice, and non-maleficence—with the new challenges posed by neural interface technologies.

Discussion

The results of this review show that the ethical debate on neurotechnologies constitutes an interdisciplinary field in consolidation, interrelating neuroscience, philosophy, law, and public policies. The growing integration between brain and machine through brain-computer interfaces and deep brain stimulation has expanded the therapeutic and experimental scope of these technologies, while intensifying traditional bioethical dilemmas concerning autonomy, identity, and privacy [38,39].

Autonomy and informed consent remain among the most complex issues. Patients submitted to invasive neural interventions frequently face cognitive limitations that compromise their full understanding of the subjective risks and changes resulting from the procedure. This requires a dynamic, continuous, and revisable consent model, adjusted to the evolution of the device and the participant's own mental state [40]. The international literature has reinforced the importance of incorporating participatory and transparent approaches in the development of BCIs and DBS, recognizing the vulnerability of users and the power imbalance between developers and patients [1,34].

Personal identity and authenticity emerge as central axes in neurotechnology ethics. The cognitive and affective transformations induced by neuromodulation devices challenge the notion of a stable "self," raising reflections on psychological continuity and sense of agency [41,42]. Some authors propose that the neurotechnological experience should be understood as a form of "shared agency," in which the subject and technology co-participate in the production of actions and meanings [1]. This conception relativizes the idea of threatened authenticity and emphasizes identity plasticity as part of the mind-machine integration process [43].

The debate on mental privacy and neurorights has gained prominence recently with the advancement of BCIs capable of decoding brain patterns and inferring mental states. Neural data protection requires specific ethical-legal frameworks, as brain information carries interpretive potential that is superior to any other biometric data [44]. Proposals such as neurorights seek to ensure cognitive freedom and mental integrity in the face of the possibility of algorithmic manipulation or commercialization of neural signals [45]. This debate reflects the urgency of harmonizing technological innovations with legal instruments for the protection of cognitive dignity.

Another critical point refers to justice and equitable access. The development and application of neurotechnologies are concentrated mainly in high-income countries, which tends to reproduce structural inequalities. Recent studies note the importance of global policies for regulating and fostering translational research, to democratize the benefits of applied neuroscience and mitigate risks of technological elitism [46,47]. This perspective converges with the principle of bioethical equity, according to which scientific progress must serve the common good and not deepen social exclusions [39].

Moral and legal responsibility in neuromodulation contexts represents another emerging challenge. When devices interact directly with human will and behavior, it becomes difficult to determine full authorship of technologically mediated actions [48]. Recent ethical governance models propose structures of responsibility shared among patient, professional, and developer, in conjunction with technical traceability and algorithmic auditing systems. This approach aligns with the notion of "prospective bioethics," which aims to anticipate ethical impacts before the clinical consolidation of innovations.

In general, the literature converges on the need to institutionalize a bioethics adapted to the neurotechnological era—an ethics that is at the same time normative, regulatory, and reflective. The initiatives by UNESCO and IEEE indicate an international movement toward global guidelines on brain data governance and mental integrity; however, there are still gaps in concrete application [9]. Consistently, the *Bioética* journal has been prominent in Brazil for discussing neuroethics as an institutional field of mediation between science and society [39,43], reinforcing the importance of globally contextualizing the ethical challenges of the brain-machine interface.

In summary, the advancement of neurotechnologies demands a reformulation of classical biomedical ethics, expanding it to include cognitive autonomy, neural privacy, and mental dignity as fundamental values. Reinforced public policies, interdisciplinarity, and continuous dialogue between science and bioethics are essential ways to ensure that neurotechnological progress remains aligned with the protection of humans.

Final considerations

The present integrative review demonstrates that the advancement of neurotechnologies redefines the classic boundaries of bioethics, imposing the need for new approaches to deal with emerging dilemmas related to autonomy, identity, privacy, and justice. The transformations promoted by devices such as deep brain stimulation and brain-computer interfaces expand therapeutic possibilities, but also introduce unprecedented risks of cognitive vulnerability, neural data manipulation, and unequal access to innovations.

The reviewed studies noted the urgency of global ethical governance, founded on principles of shared responsibility, transparency, and respect for human dignity. The consolidation

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of international guidelines, such as the proposal for neurorights, constitutes a fundamental step toward balancing clinical benefits and moral risks, ensuring the responsible development of neurotechnologies. In this context, it is reinforced the need to drive interdisciplinarity between neuroscience, philosophy, law, and public policies, to guide safe, just, and humanized scientific practices.

In summary, contemporary bioethics is called upon to anticipate and mediate the social and existential impacts of the interaction between brain and machine. Keeping the ethical and regulatory debate permanently updated is an essential condition so neurotechnological progress not only expands human capabilities but also preserves the values that underpin the very meaning of humanity.

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Ricardo Ferreira Gomes – Master's student – ricardo.gomes6401@gmail.com
0009-0004-5304-3490

Rejane Laranja – Master's student – laranjarejane97@gmail.com
0000-0001-9575-4013

Jonas Byk – PhD – jonas.byk@hotmail.com
0000-0001-5854-4316

Silvania Furtado – PhD – silvaniafurtado@ufam.edu.br
0000-0003-0065-3119

Robson Amorim – PhD – amorim.robson@gmail.com
0000-0003-2391-7519

Correspondence

Ricardo Ferreira Gomes – Universidade Federal do Amazonas. Rua Afonso Pena, 1053, Centro, CEP 69020-160. Manaus/AM, Brasil.

Contribution of the authors

Ricardo Ferreira Gomes: study conception; methodological design; data collection; data analysis and interpretation; manuscript writing. Rejane Laranja: study conception; methodological design; data collection; data analysis and interpretation; manuscript writing. Silvania Furtado: critical review of the content; suggestions for manuscript improvement. Jonas Byk: manuscript review. Robson Amorim: study supervision; final manuscript review.

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