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Building resilience when neural implants are abandoned

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As neural implants become more integrated with human cognition and identity, the risks posed by their sudden discontinuation are unique and demand urgent attention.

Neural implants are transforming the treatment of neurological disorders and reshaping the boundaries between technology and human identity. But although these devices offer immense therapeutic potential, they have also given rise to a crucial ethical and societal challenge, 'neuroabandonment' – a term introduced here to describe the premature discontinuation of neural implants and their associated support systems[1]. Unlike other medical technologies, neural implants integrate deeply with the human nervous system, making their discontinuation both medically and emotionally disruptive. Here we examine the growing risks of neuroabandonment for patient wellbeing, societal trust and industry innovation, and the unique factors that distinguish neural implants from other interventions. We propose strategies to mitigate these risks, including financial safeguards, technical standardization, regulatory reforms and policy-driven interventions.

Implantable neural devices offer new therapies for neurological disorders while redrawing the lines between brain, mind and machine. Some of these technologies, such as cochlear implants, are more established, while many others are in early feasibility trials or have only recently reached the market. These devices include deep brain stimulators, spinal-cord stimulators, brain–computer interfaces and neuroprosthetics. They offer therapeutic possibilities for conditions such as Parkinson's disease, chronic pain, epilepsy and others.

Today, more neural implants are entering clinical trials and the market. In parallel, many companies are struggling to sustain operations because of multiple challenges in the field[2]. As a result, the risk of corporate insolvency in neurotechnology is high. However, the abandonment of neural implants when trials are discontinued, or when companies fail (Box 1), leaves individuals without essential medical, technical and financial support throughout and beyond their implant's lifecycle. This is not only a business failure; it also severely affects patients, has impacts on society at large and raises urgent ethical concerns.

Going forward, the rollercoaster journey of neurotechnology is likely to continue, as trials and commercialization of new implants accelerate, driven by advances in neuroscience, artificial intelligence (AI) and engineering. Substantial investments are being made, with the global brain-implant market projected to reach US $9.2 billion by 2028. These technologies aim to restore vision, facilitate communication and motor control, treat psychiatric disorders, or even aspire to enhance human mental capacities. But not all ventures will succeed; failure is inherent to innovation, and as commercial expectations grow, the abandonment risk rises.

The unique severity of neuroabandonment

The discontinuation of neural implants reveals a harsh reality (Box 1): when companies fail, implant users are left vulnerable. Neural implants are transforming not only the way we treat disease but also the way in which we understand health, identity and the human condition. Their intimate link with nerve tissue means that, once implanted, they help to shape thought, emotion and agency. Hence, when such devices are abandoned, the disruption extends far beyond loss of therapeutic function to the very sense of self.

Why is the impact so deep? Neural implants affect the relationships between the body, the brain and the mind, each contributing to the shaping of an individual's 'identity integrity'[3]: the coherence, continuity and authenticity of one's self across time. In addition, the notion of human corporeality is highly relevant. The concept of corporeality emphasizes that individuals both have a body (*Körper*), the material organism, and are a body (*Leib*), the 'felt body' that grounds self-consciousness and personal identity. Protecting both the identity integrity and the corporeality of people is therefore crucial.

Neuroabandonment thus poses challenges that are likely to be greater than those seen when other treatments are withdrawn. Prior studies of drug or assistive-device discontinuation cite difficulties in patient decision-making, psychological impact and logistics[4], yet neural implants have distinctive features that further amplify the consequences of abandonment. These distinctive features are as follows:

Permanent, often irreversible, integration

Neural implants – unlike drugs or other short-term therapies – form long-term and often permanent interfaces with the brain, spinal cord or peripheral tissue. Engineered to minimize immune reaction and promote biointegration, they interact directly with neurons and induce neuroplastic adaptation. Consequently, removal is far riskier than stopping medication: any attempt to remove them could cause irreversible harm, leave lasting neurological deficits or even trigger new neurological conditions. The challenge grows over time; for instance, Neuralink's leadership noted that removal of their electrodes may be feasible within the first three months, before scar tissue forms, but beyond that period, the flexible electrode threads become embedded in neural tissue. In short, the very features that give neural implants their therapeutic power – their deep integration – also make abandonment uniquely hazardous.

Impact on personal and social identity

Unlike other medical implants, such as pacemakers, which sustain vital physiological functions, many neural implants also modulate cognitive

BOX 1

Notable examples of discontinued neural implants

Autonomic Technologies (USA) developed a promising minimally invasive therapy for migraines (managing cluster headaches). At the end of 2019, the company had collapsed and left more than 700 people alone with a complex implanted medical device. People using the stimulator and their physicians could no longer access the proprietary software needed to recalibrate the device and maintain its effectiveness, leaving them facing uncertainty[10].

EndoStim (USA and the Netherlands) is developing an implantable neurostimulation system targeting disorders of the digestive system. In October 2019, EndoStim terminated its clinical investigation[11], entered a liquidation and insolvency procedure and announced that clinical and technical support will no longer be available for the devices after 14 January 2020. Interestingly, however, in 2022 EndoStim announced that it received a 'breakthrough device' designation from the US Food and Drug Administration, and since then it has emerged from the insolvency proceeding.

NeuroControl (USA) developed the 'freehand system', an implantable neuroprosthesis designed to restore hand function in individuals with tetraplegia resulting from C5 or C6 spinal-cord injuries. The system was implanted in more than 250 individuals, providing them with the ability to perform grasp-and-release functions through functional electrical stimulation[12]. Despite the clinical success and user satisfaction associated with the freehand system, NeuroControl ceased operations in 2001 owing to financial challenges, leaving individuals with unsupported devices and without ongoing technical support.

NeuroVista (USA) developed a seizure-predicting implantable device that was trialed in 15 individuals with epilepsy; despite the device meeting its enabling criteria in 11 of 15 individuals[13], the company's 2013 bankruptcy led to the advised removal of all implants.

Nuvectra (USA) saw more than 3,000 individuals implanted with their spinal cord stimulation system for pain management. Despite its market adoption, and evidence in a case study of reducing opioid dependence, the company filed for bankruptcy in 2019. Since then, its intellectual-property assets were bought by Cirtec Medical, which in 2021 announced that they withdrew the marketing of the device and made the device's proprietary information available to any other company seeking regulatory approval for similar devices.

Retina Implant (Germany), specializing in subretinal implants for retinitis pigmentosa, ceased operations in 2019 while their technology was already implanted in 38 individuals and while their clinical trial showed promising results, with 14 of 15 trial participants experiencing improved light perception[14].

Second Sight (USA), a company whose retina implant technology was expected to transform the treatment of blindness, laid off most of its workforce in 2020, leaving its technology obsolete and unsupported for the roughly 350 people who were already using it[15].

Stimwave (USA), a manufacturer of spinal-cord stimulators, filed for bankruptcy in June 2022, leaving thousands of individuals and their physicians in a state of uncertainty. They are at present awaiting the results of a legal case, while the company's former CEO has already been convicted and sentenced.

processes, such as communication, movement, emotion and, thus, the mind. These devices enable patients to carry out essential tasks and to engage in social interactions that are fundamental to their identity and quality of life[5]. When these technologies are abandoned, patients' capacity for meaningful engagement with the world is undermined. Neural implants also have the potential to alter core aspects of personal identity, including memory, cognition and emotional regulation. In this sense, these devices become embodied elements of the patient's self[6]. When a neural implant is abandoned, patients experience a sense of loss that extends beyond physical disability. They may feel as though a part of their identity has been taken from them. This raises ethical concerns about identity integrity, particularly when abandonment results from corporate decisions.

Cybersecurity risks

As neural implants become increasingly software-driven, cybersecurity risks rise. Abandoned devices no longer receive updates, leaving them vulnerable to bugs and hacking. Vulnerabilities in pacemakers have already been documented[7] and we should learn from them; however, the stakes are higher for neural implants: a compromised device could be controlled remotely, endangering both bodily safety and mental autonomy. In addition, modern AI-powered neural implants create the closest possible integration between human and artificial intelligence. However, AI still suffers from challenges, including bias, opacity and unpredictable behaviors. This convergence amplifies existing concerns and adds new ones about agency, mental privacy and human augmentation[8].

Individual, societal and industrial implications

The challenges outlined above show that neuroabandonment raises concerns at multiple levels.

Individual level. Neuroabandonment threatens patients' physical and mental health. Neural implants not only sustain life; they are also life-enhancing technologies that shape human cognition and social interaction. When these devices fail, people are left dealing with a range of physical and psychological consequences. As seen in the case of Rita Leggett[9], a patient who described the removal of her brain implant as akin to losing a part of herself, the psychological toll of abandonment can be devastating and traumatic. This highlights the need for both mental-health and daily-life support for affected individuals. If the issue of neuroabandonment is not successfully addressed, people may be

discouraged from adopting future neurotechnological devices owing to awareness of this risk.

Societal level. Neuroabandonment threatens public trust and social cohesion. Because neural implants modulate core traits that are essential for social interaction, their failure can spark fears about mind control and undermine acceptance of neurotechnology. Distrust can spread not only toward manufacturers and healthcare professionals who offer these implants, but also toward patients themselves, who may be stigmatized as 'dehumanized cyborgs'. Furthermore, equity and accessibility questions arise: who will be abandoned and who can afford alternatives? Will insurance cover the costs? Cultural norms could shift as well: if living with inert implants becomes normal, as an unavoidable consequence of deep-technology treatments, the social and legal value of bodily integrity may erode.

Industry level. Neuroabandonment could undermine trust in the neurotechnology sector. However, imposing additional regulations on an already heavily regulated field could have the opposite effect: to hinder innovation or drive manufacturers away. New safeguards must therefore strike a careful balance. Ultimately, companies should instill confidence by guaranteeing long-term implant support and prioritizing patient safety. Without that assurance, public acceptance of neurotechnology may wane, reducing its adoption and depriving society of its benefits.

Building resilience

Addressing neuroabandonment requires a systematic analysis of past failures to develop actionable recommendations. Such an analysis would identify the root causes of abandonment and evaluate the feasibility of interventions to target those causes. Although such analysis is still pending, the following measures are proposed as possible solutions for building resilience.

Financial measures. Financial safeguards could mitigate the consequences of neuroabandonment by ensuring that resources are available for long-term device support. Potential measures include dedicated funds, escrow accounts or mandatory insurance coverage to secure maintenance and repair capabilities. Legislation requiring investors or shareholders in neurotechnology to contribute to safety nets could further distribute responsibility and reduce the risk to patients.

Technical standardization. Standardizing crucial device components, such as neuro-access mechanisms, could enhance interoperability and allow third parties to perform repairs, even after a manufacturer ceases operations. Drawing from successful initiatives such as the European Union's USB-C regulation, such measures could improve device sustainability. Additionally, establishing secure repositories for prototype designs and technical documentation could enable international repair services to maintain devices. For software and AI systems, companies could deposit detailed 'masterplans' in these repositories, ensuring continued functionality while respecting intellectual property rights.

Regulatory approaches. Enhanced regulatory frameworks could play a pivotal role in minimizing neuroabandonment risks. Regulatory bodies could mandate ethical analyses as part of product approval. These analyses would highlight abandonment risks and propose mitigation strategies. Furthermore, requiring manufacturers to establish clear 'exit' strategies would ensure continuity of care. In addition, strengthening patient interests by formally recognizing them as stakeholders, rather than as mere beneficiaries, within frameworks such as medical-device regulations would better protect their rights, particularly in cases of manufacturer insolvency.

Legal safeguards. Legal mechanisms could complement financial and regulatory measures by formalizing obligations for companies to maintain device support. For example, contractual obligations could require established companies to allocate a small portion of their workforce to support devices from failed companies. Such provisions would spread the support burden and preserve patient access.

Policy interventions. Policy-based solutions could empower public or non-profit organizations to act as independent guarantors, stepping in to manage and resolve failures in the neurotechnology sector. Governments could also promote public–private partnerships to build robust support systems for high-risk technologies, ensuring societal resilience in the face of market disruptions.

Neuroabandonment is no longer hypothetical; the cases presented here show that many individuals have already been left with unsupported implants. Moreover, because these devices integrate closely with the nervous system, their abandonment carries ethical implications far beyond those of most medical technologies, harming patients and eroding public trust in the neurotechnology sector. By integrating financial, technical, regulatory, legal and policy-based strategies, stakeholders can foster a resilient neurotechnology ecosystem that protects individuals, promotes ethical innovation and builds societal trust.

A coordinated effort is essential, involving patient groups, industry, clinicians, ethicists, regulators and insurers. A systematic study of past failures must first clarify root causes. Ultimately, every new neural implant should include a documented 'exit' strategy to guarantee patient support if the manufacturer disappears. Clinical and post-market guidelines must be reviewed to secure competence in informed consent, mental privacy and lifelong care, while regulatory safeguards should remain realistic for industry so that protection does not stifle innovation.

We predict that, if not addressed now, neuroabandonment will become more frequent, more impactful and ethically more complex in the future. The measures proposed here can serve as a starting point for building a resilient neurotechnology ecosystem — one that realizes the benefits of neurotechnology without abandoning those it is meant to help.

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Competing interests

G. K. is a co-founder, board member and shareholder at Brainscape Medical (Geneva, Switzerland). T.S. is a co-founder of CorTec (Freiburg, Germany) and neuroloop (Freiburg, Germany) and is a member of their scientific advisory boards.