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Review

# Insinuating electronics in the brain

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ABSTRACT

There is an expanding interface between electronic engineering and neurosurgery. Rapid advances in microelectronics and materials science, driven largely by consumer demand, are inspiring and accelerating development of a new generation of diagnostic, therapeutic, and prosthetic devices for implantation in the nervous system. This paper reviews some of the basic science underpinning their development and outlines some opportunities and challenges for their use in neurosurgery.

## Introduction

Charles Babbage pioneered early mechanical computing devices in the 1820s.[1] Today's computers have a predominantly microelectronic substrate and their performance, efficiency, and affordability continue to improve rapidly and predictably[2,3] (see Fig. 1A). By the 1980s, this allowed development of *portable* electronic devices. Now even smaller and more energy-efficient microelectronic devices are enabling the transition from portable to wearable to *implantable*. In tandem with an improving understanding of neuro–biotic interfaces and the computational machinery of the brain, such advances are enabling new ways to invasively monitor, interact, and intervene with nervous systems.

Micro-electromechanical systems (MEMS) combine miniaturized mechanical and electromechanical elements.[4] Their physical dimensions range from several millimetres to well below one micron. The functional elements of MEMS are shown in Fig. 1B. MEMS transduction components (microsensors and microactuators) convert energy from one form to another and have particular relevance in biomedical applications. A wide range of microsensors now exist, including those that measure temperature, pressure, magnetic fields, radiation, impedance, inertial forces, and different chemical species. Micro-actuators include tools capable of ablating tissue (using heat, light, or ultrasound, for example) and tools for controlled delivery of bioactive molecules (such as chemotherapy or neurotransmitters). Others include micro-valves to control fluid flow, optical switches to modulate or redirect light, and micro-resonators.

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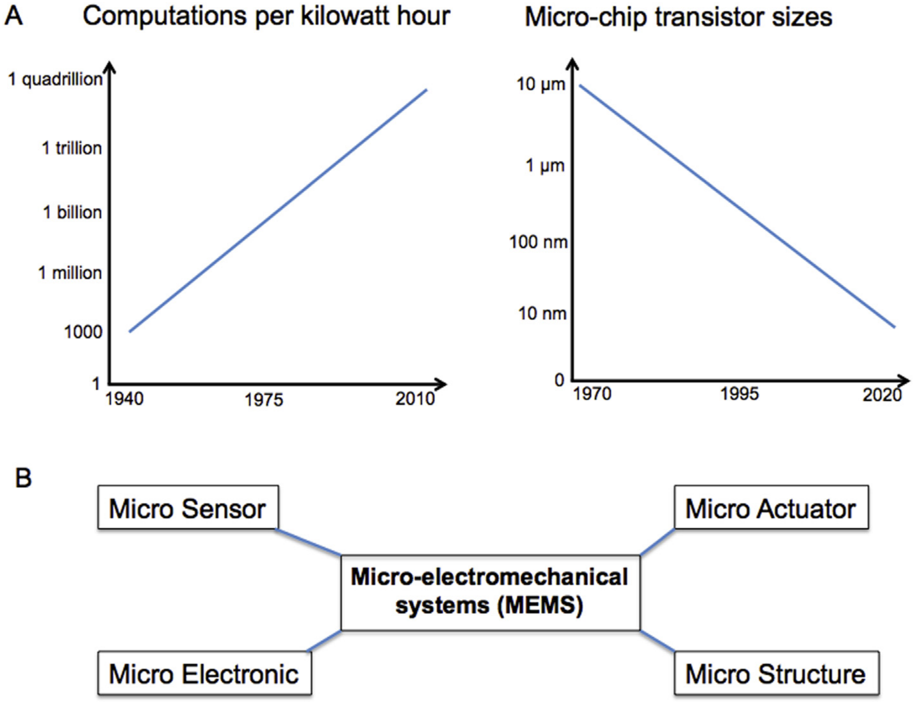

**Fig. 1 – (a) Trends showing the rapid and persisting increase in computational power, and decrease in microchip size, in recent decades (based on data from Refs. [2,3]). (b) The component parts of the archetypal micro-electromechanical system.**

The production methods used for MEMS mirror those used for batch fabrication in the integrated circuit industry. Once production reaches scale, this serves to lower production costs and increase reliability and functionality. MEMS (and their nano-scale equivalent, NEMS) enable the development of complete systems-on-a-chip: sensors collect information that is processed locally and used to direct actuators that alter aspects of the surrounding environment. In an implanted *in vivo* context, this model has numerous potential applications.

Usefully, the nervous system itself is governed by electronic signals: ions in solution move through membrane-bound channels in neurons, whilst electrons move within the solid-state lattices of microelectronic semiconductors. Hybridising the two systems to create a neuro–bionic interface is therefore a logical proposition, though one with multiple biological and engineering challenges. Beyond offering new ways of monitoring and intervening, hybrid systems can link neurons to prosthetic effectors; thereby offering a means of restoring function by circumventing an area of nervous system damage. This addresses the nervous system's very restricted capacity to recover or reorganise, and may finally allow neurosurgeons to mitigate *primary* brain injury. This paper outlines some of the challenges and opportunities for CNS-implanted MEMS.

## Challenges

The CNS is an unforgiving environment in which to intervene at all, let alone implant electrical devices. Complex neuroanatomy on a relatively small scale, notable vascularity, and conspicuous fragility are all challenges to implantation. Beyond these pragmatic surgical considerations, a fundamental challenge for all bionic systems is the interface between living tissue and implanted material.[5] The host response to implantation of a foreign body tends to result in encapsulation. In the brain this takes the form of gliosis, resulting in insulation of the electrode or implanted component.[6] Ideally, implanted systems would induce minimal foreign body response, allowing an intimate, long-term interaction with specific cells (or even subcellular components). These challenges have spurned extensive materials science and electrical engineering research that aims to engineer a sympathetic interaction and long-term functional connection between neurons and microelectronic systems.

For neuro-prosthetic devices, there is also the pre-requisite to interface with the *computational* apparatus of the brain. This is a massive challenge. The human brain contains ~86 billion neurons, each with ~7000 synapses, cooperatively performing $\sim 12 \times 10^{15}$ computations per second.[a] Different neurotransmitter types, the variable influence of glial cells, and a dynamic ultrastructure complicates the situation further. Moreover, neuronal organisation and connectivity evolve during development, ageing, and in response to pathology.

Whilst electronic signalling is central to both domains, there remain fundamental differences in computational

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[a] This approximation is based on assumptions of 86 billion neurons, connected via 7000 synapses per neuron, firing at an average frequency of 20 Hz, resulting in $1.204 \times 10^{16}$ firing events per second. Moreover, this approximation fails to appreciate other "calculations" attributable to glia:neuron interactions or neuropeptides, for example.

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