

The paradigm shift in chip implantation technology: From passive treatment to active enhancement

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Abstract:

This article systematically reviews the development history of chip implantation technology, from the early medical-oriented passive treatment technology to the modern active enhanced application paradigm shift. By analyzing typical cases such as pacemakers, insulin pumps and cochlear implants, this article deeply and fully expounds the principles of passive medical treatment techniques, the effects to the human life, and limitations of medical treatment techniques. At the same time, this article also explores technological breakthroughs in new applications such as enhanced brain-computer interfaces, memory enhancement, and emotion regulation. By analyzing the difference between passive treatment and modern one, this paper finds that the fundamental reason for the paradigm shift lies in core technologies such as chip miniaturization, neural signal processing, and closed-loop feedback control. Noticeably, they gradually correspond the human's increasing demands for daily life. Finally, this paper discusses the social impact of paradigm shift and the future development direction of chip implantation technology.

Keywords: Passive treatment, active enhancement, paradigm shift.

1. Introduction

The birth of chip implantation technology stems from the dual demands of modern medicine for precise treatment and human functional reconstruction [1]. The development of this technology was initially driven by the need to treat neurological diseases and repair peripheral nerve injuries [2]. Specifically, in the middle of the 20th century, traditional medical methods demonstrated certain limitations when deal-

ing with complex diseases, especially in situations where real-time monitoring or intervention was required [3]. For instance, patients with heart disease need to constantly monitor changes in their heart rate, while those with diabetes need to frequently adjust their insulin dosage. However, breakthroughs in semiconductor technology have provided new ideas and solutions for these complex diseases. The concept of early chip implantation technology mainly focused on using micro-sensors and processors to

record physiological data [4], and sending the information to external devices for analysis via wireless transmission [5]. Simply put, through the direct interaction between microelectronic devices and the human nervous system, humans can precisely monitor and regulate physiological signals. Furthermore, during the 1960s to 1990s, advancements in brain science also provided a significant impetus for the rise of chip implantation technology. At that time, brain-computer interfaces mainly adopted non-invasive EEG or preliminary invasive electrodes to collect signals. This technology initially reveals the possibility of interaction between the human brain and external devices through the collection and processing of electrical signals [6]. This further promoted the feasibility study of human chip implantation technology.

From simple chip implantation to today's complex and diverse implantable devices, chip implantation technology has undergone multiple key stages of technological evolution and material breakthroughs. The initial stage was dominated by single-function implantable devices, such as pacemakers and cochlear implants and other passive medical equipment. These devices aim to treat specific diseases; for example, pacemakers regulate heart rhythms and cochlear implants restore hearing. However, due to the limitations of manufacturing techniques and technological levels at that time, these early devices were large and had single functions, making it difficult to meet diverse demands

Implantable chips have become smaller, smarter, and more functional since the 21st century, because of advances in microelectronics and nanofabrication. For instance, implantable cardiac pacemakers have evolved from their initial huge size to miniature intelligent devices no larger than capsules [7]. It simultaneously features a higher energy efficiency ratio and more precise monitoring capabilities. In addition, the advancement of brain-computer interface technology has given rise to the application of enhanced implantable chips, such as the highly integrated brain-computer interface system developed by Neuralink. This system can collect many neural signals in a short time and achieve complex human-computer interaction tasks [8]. In recent years, the introduction of artificial intelligence chips has further expanded the application scope of implantable chips. AI chips can not only efficiently process complex physiological data, but also provide real-time decision support through deep learning algorithms. It offers new possibilities for personalized medicine and proactive augmentation.

Overall, the development history of implantable chips reflects a technological paradigm shift from single-function to multi-functional integration and from passive treatment to active enhancement. In the development history of im-

plantable chips, there are significant differences in purpose and scope between passive and active chip implantation. This difference reflects the transformation process of chip implantation technology from the early simple treatment needs to the modern enhanced capabilities. Passive chip implantation is mainly used for diagnosing and treating diseases, and its core objective is to improve patients' health conditions through external intervention. In contrast, active chip implantation goes beyond the scope of traditional medicine, with the aim of enhancing human cognitive, emotional, and physical abilities through technological means.

2. Traditional application: Early medical-oriented implantable technology

Early medical-oriented implant technologies mainly focused on functional repair and life support fields. Among them, the main representative implant technologies include pacemakers, cochlear implants, drug infusion pumps, artificial joints, and deep brain stimulation. These early implant techniques exhibit three characteristics: passive repair, electromechanical priority, and single-item intervention. Their main purpose is to replace or compensate for the impaired physiological functions of the human body, and they mainly rely on technological breakthroughs in electronic engineering and materials science. In addition, these early devices merely output signals or drugs, lacking sufficient physiological feedback. Next, the author will take pacemakers, insulin pumps and cochlear implants as examples to explain the working principles, working modes, effects, and impacts of early technologies.

2.1 Pacemaker implantation

2.1.1 The principle and working mode of pacemaker implantation

Pacemaker implantation technology uses electrical pulses to stimulate the heart and maintain a normal rhythm. Specifically, a pacemaker regulates the heart rhythm by stimulating the contraction of the heart muscle through electrical signals. Under normal circumstances, the heart's sinoatrial node generates electrical signals that trigger the contraction and relaxation of the heart muscle. However, under certain pathological conditions, such as bradycardia or conduction block, the electrical signal conduction of the heart is affected, leading to arrhythmia or even cardiac arrest. The pacemaker senses the heart's electrical activity and releases pulses to restore a normal rhythm [9]. In simple terms, the working modes of pacemakers can be divided into single-chamber pacing and dual-chamber pacing. Single-chamber pacemakers usually only stimulate the

right ventricle to be suitable for simple ventricular conduction disorders, such as chronic atrial fibrillation with a slow ventricular rate. However, dual-chamber pacemakers simultaneously stimulate the right atrium and right ventricle, which can more precisely simulate the physiological rhythms of the heart, such as sinoatrial node dysfunction and atrioventricular block [10].

2.1.2 The effect and impact of pacemaker implantation

References

Pacemaker implantation has shown significant effects in improving the quality of life of patients, especially in enhancing activity ability and alleviating clinical symptoms. For instance, a study on patients with bradycardia demonstrated that the average exercise tolerance of these patients increased by 25% to 35% after pacemaker implantation, and symptoms such as fatigue and dizziness were significantly alleviated. The patient's ability to perform daily living has significantly improved [11]. In addition, pacemakers can significantly reduce the risk of sudden death caused by arrhythmia, thereby prolonging the survival time of patients. These positive clinical outcomes have made pacemakers an important component in the treatment of heart disease. From the perspective of the medical system, the wide application of pacemakers has changed the traditional treatment model for heart diseases. On the one hand, the implantation of pacemakers has enabled many patients who previously needed long-term hospitalization to return to a normal life, thereby reducing the pressure on medical resources. On the other hand, its efficient disease management capabilities also provide support for the overall optimization of the medical system. The U.S. saw a 43% drop in arrhythmia-related deaths from 1980 to 2010 as pacemakers became more common. This data fully demonstrates the important value of pacemakers in the medical field [12]. However, the long-term

application of pacemakers also faces some challenges, such as infection risks and battery life limitations, which still need to be addressed through technological innovation.

2.2 Insulin pump

2.2.1 The mechanism of action of insulin pumps on diabetes

An insulin pump is a medical device that precisely controls blood sugar by simulating the insulin secretion pattern of the human body. The insulin pump consists of a drug storage tank, an infusion pipeline and a control system. The device stores insulin in a reservoir, delivers it through a tube, and adjusts the dose based on preset levels and real-time glucose data. It can continuously monitor the patient's real-time blood sugar level and adjust the insulin infusion volume. And as an alternative system to the artificial pancreas, the insulin pump can be set to different basal rates in segments for 24 hours to simulate the physiological basal secretion. Under normal human conditions, the pancreas secretes basal insulin and mealtime insulin in response to changes in blood sugar concentration to maintain stable blood sugar levels. However, due to the impaired function of the islets in diabetic patients, they are unable to secrete insulin effectively. Therefore, they need to meet the body's demands through exogenous supplementation. The insulin pump, through continuous subcutaneous insulin infusion technology, can simulate the physiological secretion pattern of the pancreas. So, it can achieve more precise blood glucose management. Specifically, CSII successfully replicated the β -cell function of a healthy pancreas through a biphasic infusion mode of basal rate and large dose at meal times. Therefore, it successfully simulated the secretion pattern of the human pancreas. Fig.1 shows that the insulin pump precisely controls the blood sugar level through CSII technology.

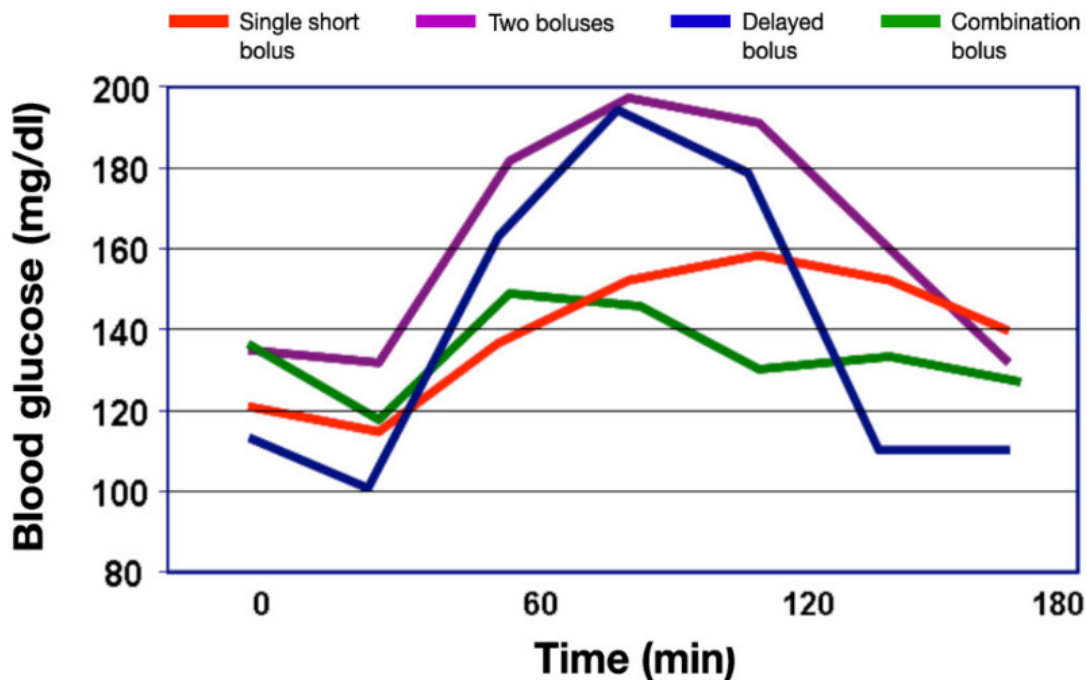


Fig. 1. Postprandial glycemic excursions with four different types of prandial insulin boluses in nine patients with type 1 diabetes on CSII [13]

2.2.2 The application significance of insulin pumps

The breakthrough of the insulin pump is that it significantly improves blood sugar control through a precise insulin infusion mode, while enhancing the quality of life of patients. Compared with traditional injection therapy, insulin pumps can more flexibly simulate physiological insulin secretion. Through adjustable basal rates and on-demand high-dose infusion, they can effectively address complex blood glucose fluctuations such as postprandial hyperglycemia. Clinical studies have confirmed that insulin pump therapy can reduce HbA1c in patients with type 1 diabetes by 0.5% to 1.5% and decrease the risk of severe hypoglycemia by 30% to 50%. In addition, the portability and intelligent design of the insulin pump have significantly enhanced the convenience of treatment, freeing patients from the hassle of frequent injections. It is particularly suitable for high-risk groups such as children, pregnant women, and those with large fluctuations in blood sugar [14].

2.3 Cochlear implantation

2.3.1 The working principle of restoring hearing

Cochlear implantation is a neural prosthesis device that restores partial hearing by electrically stimulating the auditory nerve. This device is mainly suitable for patients

with severe or extremely severe sensorineural deafness. It mainly helps patients restore some of their hearing through three key steps. The first part is sound acquisition and signal processing. Specifically, its external microphone can capture ambient sounds and the speech processor can convert the captured sound waves into digital signals. Secondly, the signal processing algorithms of the cochlea, such as frequency band division and noise suppression, can extract key acoustic features and optimize the intelligibility of speech. The second crucial step is the conversion and transmission of electrical signals in the cochlea. After that, the processed signal is sent to the receiver implanted in the body via electromagnetic induction through transdermal wireless transmission. Then, the receiver decodes the signal and converts it into a sequence of electrical pulses. The final step is electrical nerve stimulation. Specifically, the electrical pulse sequence is converted into an electrode array. Then, the electrode array is inserted into the cochlear tympanic stage, bypassing the damaged hair cells and directly stimulating the spiral ganglion cells. Finally, the electrical signals are transmitted through the auditory nerve to the auditory cortex of the brain, forming artificial auditory perception. Fig.2 presents the entire process of the cochlea from signal reception to signal processing.

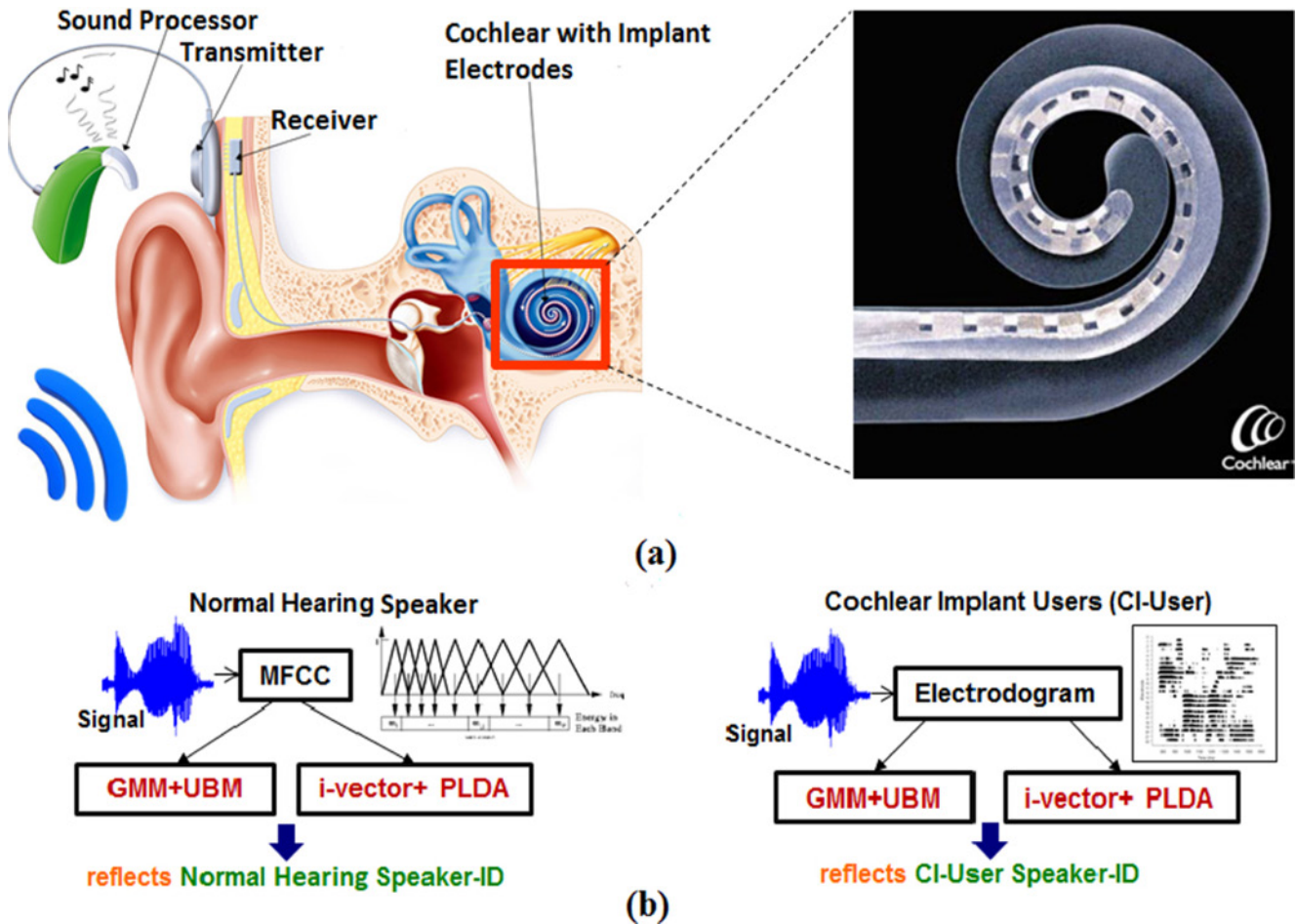


Fig. 2. Basic block diagram of ACE processing strategy used in this study to simulate the CI-users signal [15].

2.3.2 Application effects and limitations

In the early medical implant system, cochlear implants had an outstanding positive impact. Firstly, there is no doubt that cochlear implantation has indeed helped many patients restore some of their hearing. According to the survey statistics, the speech recognition rate of most users in quiet environments can reach 70% to 90%, and some patients are close to the normal hearing level [16]. In addition, patients with cochlear implants can also recognize daily sounds such as alarm sounds and knocking on doors. This will enhance the safety of patients' lives. Most notably, the language ability of deaf children (aged 1-3) who received early implantation is close to that of normal children [17]. Although cochlear implantation technology has brought revolutionary changes to patients with severe hearing loss, it still has many limitations. The frequency resolution of the cochlea is limited. The current electrode

array typically has only 12 to 22 stimulation channels, which is far less than the fine frequency analysis capacity of about 3,500 inner hair cells in a normal cochlea. Therefore, the patient's musical perception is severely limited and it is difficult for them to distinguish complex harmonies. At the same time, the patient's recognition rate for emotional tones in language decreases by 30% to 40%, such as rising tones in interrogative sentences [18]. Not only that, cochlear implantation technology is confronted with the challenges of surgery and long-term maintenance. During the operation, there will be facial nerve damage because the cochlear base gyrus borehole is adjacent to the vertical segment of the facial nerve. The incidence rate of this incident remains at 1.8% to 3.5%, slightly higher among children than adults. Moreover, during the surgery, 4.2% of the patients will still experience tympanic membrane perforation and ossicular chain injury, which can lead to residual loss of conductive hearing [19].

3. New application: Actively enhance conversion

3.1 Enhanced brain-computer interface

The technical core of the actively enhanced brain-computer interface is based on three aspects: the acquisition of neural signals, the precise recognition of decoding algorithms, and the innovation of instruction execution.

3.1.1 Neural signal acquisition technology

For signal acquisition, compared with traditional neural signal acquisition, the current multimodal fusion technology can collect signals more accurately and promptly. The most mainstream technologies today are invasive acquisition technology, non-invasive acquisition technology and hybrid acquisition technology.

Invasive brain-computer interface technology involves directly implanting electrodes into the cerebral cortex or neural tissue through surgery to capture neural electrical activity with ultra-high precision. Representative technologies include cortical electroencephalogram and Utah electrode array. Its core advantage lies in breaking through the attenuation of cranial signals, enabling fine motor control and deep brain region reading and writing. However, it faces challenges such as surgical risks, tissue rejection reactions, and signal attenuation over time.

Secondly, non-invasive brain-computer interface technology collects electroencephalogram signals on the scalp surface through external devices, such as EEG headcaps, without the need for surgical implantation. It has the advantages of being safe, non-invasive, and easy to use. Its typical representative applications include high-density electroencephalogram and functional near-infrared spectroscopy. These applications can monitor brain activity in real time, but due to the attenuation of cranial signals, their resolution is relatively low and they can only identify brain regional-level activities.

Finally, the hybrid brain-computer interface technology combines the advantages of both invasive and non-invasive methods. This technology can reduce surgical risks while improving signal quality. The most typical representative technology is the “neural dust” implanted in blood vessels. Neural Dust is a miniature wireless sensor that uses ultrasound for power and data transmission. This technology uses tiny sensors to record nerve and muscle signals with high resolution over time [20].

3.1.2 Neural signal processing

Neural signal processing is the core link for achieving high-precision control in brain-computer interfaces. It requires the conversion of raw neural activities into execut-

able instructions through AI-driven multi-level algorithms. Firstly, AI employs ICA and wavelet transform to eliminate biological noise interference, then extracts feature patterns such as P300 waves and γ oscillations. Finally, it achieves millisecond-level intent recognition through deep learning models like the CNN-RNN hybrid architecture, such as the Stanford University LSTM decoder. Overall, the signal processing of brain-computer interfaces is divided into three steps: preprocessing, feature extraction, and intelligent decoding [21]. This process has enabled paralyzed patients to type with their minds, reaching up to 90 characters per minute at the fastest. Its key technology analyzes brain signals in both space and time: CNNs process regional distribution, and RNNs analyze changes over time.

3.1.3 Signal conversion

Signal conversion technology transforms decoded neural instructions into feedback signals that can enhance brain function, mainly relying on three types of innovations: neural stimulation technology (such as closed-loop DBS for precise regulation of memory brain regions and non-invasive TMS for improving concentration), new biomaterials (graphene electrodes to reduce tissue damage), and brain-cloud interfaces (enhancing brainpower through cloud supercomputers). These technologies are breaking through the limitations of “one-way reading” and building enhanced loops with two-way interaction. They can not only interpret thoughts but also write optimization instructions to the brain. However, cutting-edge directions such as cloud-based brain interaction still face security controversies.

3.2 Experiments and cases in the field of memory enhancement

Memory enhancement is an important application scenario of neural enhancement. Chip implantation enhances functionality by regulating memory encoding and consolidation, and finally extracting loops, but it is accompanied by security risks.

Animal experiments provide direct evidence for the mechanism of memory enhancement. In 2011, the Berger team implanted a “hippocampus prosthesis” based on a MOS-FET chip into the hippocampus of rats, successfully simulating the information processing function of the CA3-CA1 neural pathway. This enabled drug-suppressed rats to regain spatial memory ability and even perform better than the normal state. Fig.3 shows the entire process of the hippocampus of rats and the recovery of spatial memory. In 2018, the team further verified this technology in experiments on macaques. By real-time recording and electrical stimulation of the hippocampus, the accuracy rate of

macaques in visual memory tasks increased by more than 40% [22]. Research found that this chip significantly enhances the efficiency of memory encoding and retrieval by precisely simulating the neural signals transmitted from the CA3 region to the CA1 region. This technology has

demonstrated potential therapeutic value in clinical trials for patients with Alzheimer's disease and brain injury. The hippocampal chip implantation system developed by the American Kernel Company.

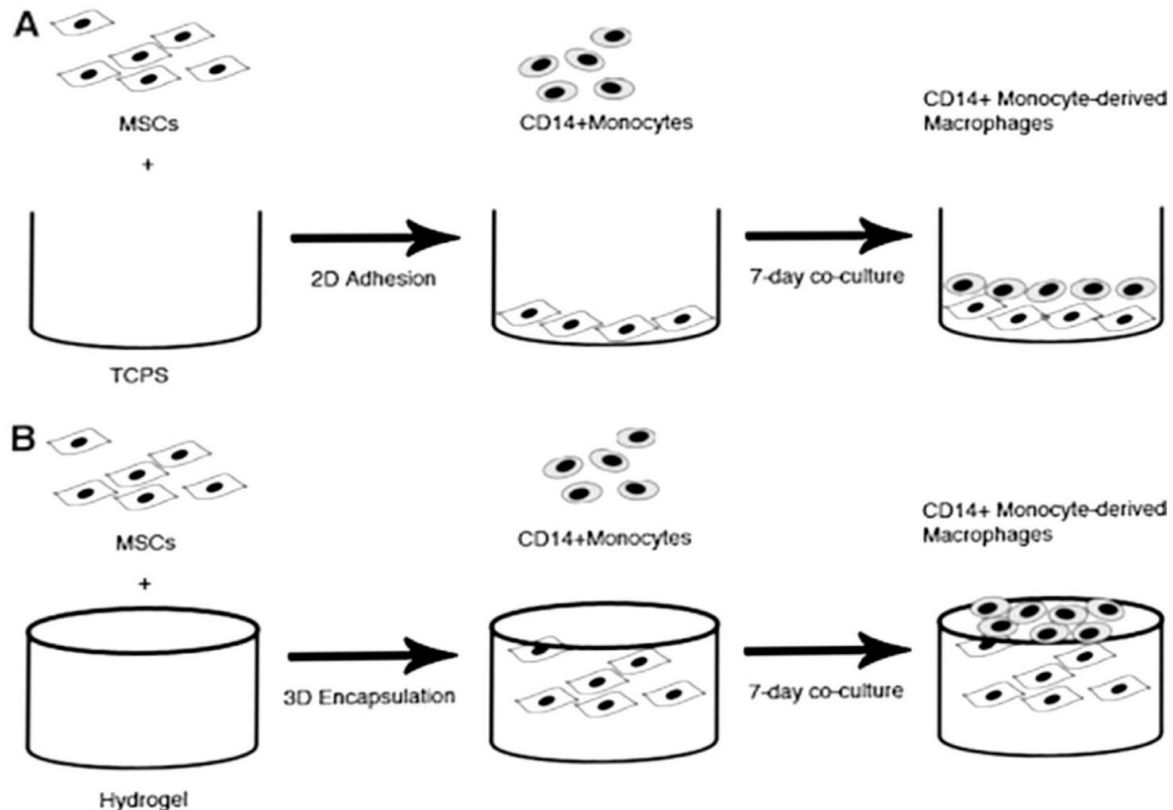


Fig. 3. Schematic drawing of the coculture system developed in this study. Mesenchymal stromal cells (MSCs) were expanded in culture to passages 4–7. MSCs were plated in 2D on tissue culture polystyrene (TCPS) at a concentration of 1×10^5 cells/well (A). MSCs were encapsulated in 3D Carbylan–GSX at a concentration of 2×10^6 cells/1 mL (B). Purified CD14+ monocytes were added to the surface of the MSC-gel construct (1×10^6 cells) and maintained in culture for 7 days to generate macrophages [23].

3.3 Emotion regulation and cognitive improvement

The active regulation of emotions and cognition is based on a closed-loop intervention mechanism of “recording - decoding - regulation” [24]. Deep brain stimulation lowers HAMD-17 scores in treatment-resistant depression by regulating amygdala activity with implanted electrodes [25]. Meanwhile, it applies high-frequency stimulation to the dorsolateral prefrontal cortex, thereby significantly improving the attention performance of ADHD patients. Responsive neural stimulation systems, like NeuroPace, detect specific brain patterns and deliver targeted stimulation. This not only improves the performance of cognitive tasks but also promotes the structural remodeling of neu-

ral networks. Neuroimaging evidence indicates that these intervention effects are closely related to the functional connectivity reorganization of the default mode network and the central executive network.

4. Core breakthroughs driven by technology

The rapid development of modern medical implant technology is inseparable from the breakthrough progress of a series of key technologies. These core technologies not only drive the performance improvement of traditional medical implant devices, but also lay the foundation for new active enhanced implant technologies. The author

will conduct a detailed analysis of how these core breakthroughs, such as chip miniaturization and low-power consumption technology, closed-loop feedback control technology, and neural interface technology, have driven the development of medical implant technology. Moreover, how these core technologies drive the paradigm shift in medical implant technology.

4.1 Miniaturization of chips, low power consumption, and wireless communication

4.1.1 Miniaturized chips break through spatial limitations

The breakthroughs in miniaturization and low-power consumption technologies are the foundation for the wide application of medical implant devices. With the advancement of semiconductor technology, the size of chips is

constantly shrinking, while power consumption is continuously decreasing. Modern implantable chips have been able to achieve nanoscale processes, reducing the chip size to 1/1000 of that of traditional chips while lowering power consumption to the microwatt level. Fig.4 presents the manufacturing process and principle of nanoscale chips. Overall, this breakthrough enables the implanted device to operate for a longer period of time while reducing the burden on the patient's body. Meanwhile, the advancement of low-power technology has significantly extended battery life. The battery life of modern pacemakers can reach over 10 years, which leads to a significant reduction in the frequency of pacemaker replacement surgeries. Similarly, for cochlear implants, miniaturized chip technology enables the implant part to be completely hidden behind the ear, with almost no impact on the patient's appearance.

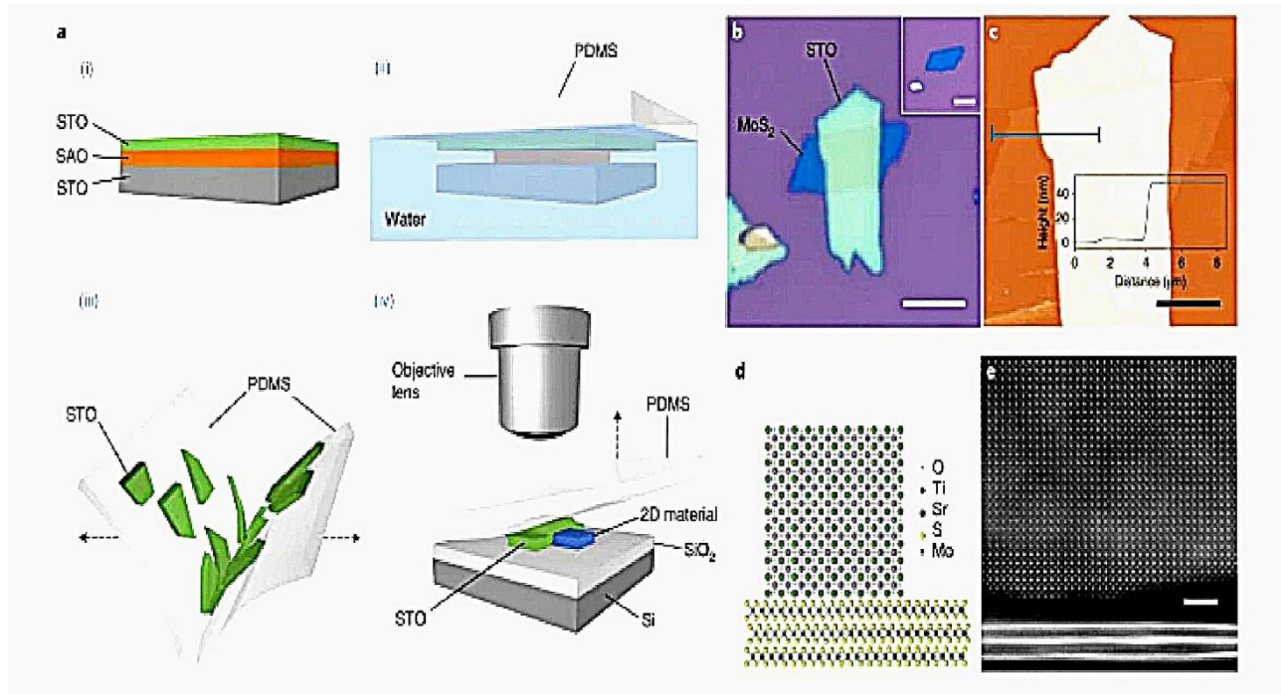


Fig. 4. a, Schematic of the fabrication process: (i) sequential PLD growth of SAO and STO on a bulk STO substrate; (ii) the surface of the STO thin film is covered with a PDMS sheet and the stack is then floated in a DI water bath to dissolve the sacrificial SAO layer; (iii) the PDMS sheet supporting the STO membrane is laminated with another PDMS sheet and peeled off slowly, yielding STO flakes on both PDMS sheets; (iv) a STO flake is aligned and laminated, under a microscope, onto a 2D material on SiO₂/Si. The PDMS sheet is then peeled off, leaving STO on SiO₂/Si. b, Optical image of a representative STO–MoS₂ heterostructure on SiO₂/Si. The inset displays the optical image of the original MoS₂ flake. Scale bars, 10 μm. c, AFM height image of the heterostructure shown in b. Scale bar, 5 μm. The inset shows the height profile along the marked line, from which the thicknesses of MoS₂ (3.4 nm) and STO (45.9 nm) were extracted. d, Schematic of three-dimensional cubic and 2D layered crystal structures of STO and MoS₂. e, Cross-sectional HAADF-STEM image of an STO–MoS₂ heterointerface. Scale bar, 2 nm [26].

4.1.2 Wireless communication technology

Wireless communication technology has completely transformed the modern medical model through various protocols, such as 5G and so on. Specifically, in clinical applications, the ultra-low latency and high bandwidth of 5G networks have enabled remote robotic surgeries and AR/VR medical training. Moreover, Bluetooth Low Energy technology supports real-time data transmission between wearable devices and implantable medical devices. Not only that, the medical Internet of things connects hospital equipment via Wi-Fi 6 to achieve intelligent early warning of the multi-parameter monitoring system in the IC. These technologies not only enable remote diagnosis and treatment to reach remote areas, but also reduce the hospitalization rate of diabetic patients through applications such as continuous blood glucose monitoring.

4.2 Neural signal processing technology and closed-loop feedback control technology

4.2.1 Neural signal processing technology

High-quality neural interface technology serves as a key bridge connecting the nervous system with external devices, and it is crucial for enhancing the accuracy of neural signal acquisition and stimulation. In terms of neural signal acquisition, high-quality neural interfaces can more accurately capture the weak electrical signals emitted by neurons. By adopting highly sensitive electrode materials and advanced signal processing algorithms, neural interfaces can effectively filter noise and extract useful neural signal information. High-quality electrode arrays cover more of the cortex, monitor multiple neuron groups at once, and interpret brain signals more accurately. In terms of neural stimulation, high-quality neural interfaces can precisely transmit the electrical signals generated by external devices to the target neurons, achieving precise regulation of neural functions. This is important for treating neurological diseases like Parkinson's and epilepsy. Precise neural stimulation regulates neuron activity, reduces symptoms, and improves quality of life. In addition, in the field of neurorehabilitation, high-quality neural interface technology can help patients restore damaged neural functions and promote neural remodeling and functional reconstruction.

4.2.2 Closed-loop feedback control technology

Closed-loop feedback control technology is a control strategy that adjusts the system input based on the output information of the system. In the field of neural technology, it can achieve precise regulation. In a neural interface system, closed-loop feedback control technology can adjust the parameters of neural stimulation in real time

based on the collected neural signals. For instance, the closed-loop feedback control system can detect abnormal brain activity and automatically adjust stimulation to restore normal rhythm of neural activity. This ability of precise regulation has significant application value in the treatment of neurological diseases and neurorehabilitation. In Parkinson's treatment, the system adjusts deep brain stimulation in real time based on movement and brain signals to better control tremors and rigidity. In neurorehabilitation training, closed-loop feedback technology can adjust rehab equipment and training plans in real time to improve recovery.

4.3 Support for paradigm shift

The development of high-quality neural interface technology and closed-loop feedback control technology will have a paradigm shift impact on neuroscience and related fields. In the field of neuroscience research, these technologies enable scientists to gain a deeper understanding of the functions and mechanisms of the nervous system. Through high-precision neural signal acquisition and precise neural stimulation, researchers can explore the interactions between different regions of the brain and reveal the mysteries of advanced neural functions such as cognition and emotion. In the treatment of neurological diseases, traditional drug therapy and craniotomy and other methods have certain limitations. However, neural regulation technology based on neural interfaces and closed-loop feedback control provides new ideas and methods for the treatment of neurological diseases. These technologies can achieve personalized treatment plans, provide precise treatment based on the specific conditions of patients, improve treatment outcomes, and reduce the occurrence of complications. In the field of human-computer interaction, high-quality neural interface technology makes the interaction between humans and machines more natural and efficient. People can directly control external devices through brain signals, achieving true brain-computer integration.

Meanwhile, the miniaturization of chips and breakthroughs in wireless communication technology have jointly driven a fundamental transformation in the medical paradigm. In terms of miniaturization, the 7nm manufacturing process has reduced the power consumption of medical chips to the microwatt level. Moreover, the medical chip, combined with bioenergy harvesting technology, has reduced the volume of the implanted device and enabled its battery life. In terms of communication technology, 5G URLLC and Bluetooth 5.3 have built a multi-level medical internet of things, and achieved seamless data connection from in-body nano sensors to cloud systems.

The miniaturization of chips has given rise to three landmark applications: leadless pacemakers, real-time closed-loop diabetes management systems, and 5G remote surgery systems. These technologies drive the medical model from passive treatment to active health management [27].

5. Conclusion

This paper analyzes the shift in implant technology from treatment to enhancement, revealing its logic, drivers, and social impact. Essentially, the paradigm shift in chip implantation technology is manifested in the gradual expansion of its application goals from the traditional “disease treatment” to “capability enhancement”. At the “passive treatment” level, chip implantation technology has played a key role in the management of various chronic diseases and functional disorders. For instance, pacemakers effectively maintain the heart’s rhythm, insulin pumps precisely control blood sugar levels, and cochlear implants restore hearing function. These technologies improve disease management, reduce risks, and enhance patient quality of life. In the direction of “active enhancement”, brain-computer as emerging technology interfaces enhance cognition, emotion, and interaction by processing neural signals in real time. This technology not only expands the boundaries of human perception and behavior, but also provides new research tools and application scenarios for cutting-edge fields. This shift is driven by advances in chip miniaturization, wireless technology, neural interfaces, and closed-loop systems. The paradigm shift in chip implantation technology has not only profoundly influenced the landscape of the medical and health industry, but also sparked extensive ethical discussions on the boundaries of “human enhancement”. As technology gradually intervenes in the regulation of human cognition, emotion and behavior, its potential social impact is becoming increasingly prominent, involving a series of core issues such as security and privacy protection. Therefore, the development of technology must strike a balance between innovation and risk to ensure that technology serves all of humanity. For the future, chip implantation devices will develop towards the nanoscale to achieve higher biocompatibility and tissue integration. Meanwhile, AI algorithms enhance neural signal analysis and adaptive control, making implanted systems more personalized and intelligent.

In conclusion, the paradigm shift in chip implantation technology is not only an inevitable outcome of technological evolution, but also a concentrated manifestation of humanity’s continuous exploration of its own cognitive boundaries and capability limits. From “passive treatment” to “active enhancement”, this process reflects the

dynamic interaction between technological progress and human needs.

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