

# Flexible electrodes for non-invasive brain-computer interfaces: A perspective



Cite as: APL Mater. 10, 090901 (2022); doi: 10.1063/5.0099722  
Submitted: 18 May 2022 • Accepted: 28 July 2022 •  
Published Online: 1 September 2022



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## ABSTRACT

At the present time, brain-computer interfaces (BCIs) are attracting considerable attention due to their application potential in many fields. In this Perspective, we provide a brief review of flexible electrode technologies for non-invasive BCIs, mainly including two types of the most representative flexible electrodes: dry electrodes and semi-dry electrodes. We also summarize the challenges encountered by the different kinds of electrodes by comparing their strengths and weaknesses in terms of manufacturing scalability, applicability, comfort, contact impedance, long-term stability, and biocompatibility. In addition, we describe some advanced configurations and suggest potential applications for non-invasive BCIs based on flexible electrodes and consider future development prospects.

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## INTRODUCTION

The brain is considered the most mysterious human organ. Due to its massive number of neurons constantly generating and transmitting electrophysiological signals,<sup>1</sup> it can store and process an ocean of information. At the present time, brain-computer interface (BCI) technology allows direct interaction of the brain with the external world without the intervention of the peripheral nervous system.<sup>2–8</sup> Since Vidal proposed his general framework in 1973, BCIs, also known as brain-machine interfaces, have been developed for decades (Fig. 1).<sup>9</sup> As shown in Fig. 2, a typical BCI comprises four functional processes: signal acquisition and amplification, feature extraction and classification, control signals, and feedback. All these processes are indispensable and face their own challenges, wherein the first step, which mainly involves device design, engineering demonstration, and methodology, is decisive for all BCI systems.

Depending on the signal acquisition method, BCIs can be divided into two categories: invasive and non-invasive.<sup>10–15</sup> The former has been used in clinical medicine, brain and neuroscience research, robotic control, and communications, aiming at

high-resolution detection and translation of intracranial electrophysiological signals such as field potential and spike signals *in vivo*.<sup>16–24</sup> However, the necessary implanting operation, possible trauma, and biocompatibility issues constitute significant barriers to commercial applications. On the other hand, due to their portability, usability, biocompatibility, and non-intrusiveness, non-invasive BCIs show more extensive application prospects for not only scientific research and medical applications but also for daily health-care and even entertainment.<sup>25–28</sup> In contrast to invasive solutions, non-invasive BCI technology focuses on cerebral cortical electroencephalogram signals, such as the motor imagery (MI), P300, and the steady state visually evoked potential (SSVEP).<sup>29–31</sup> In this case, the contact between the electrodes and the participant's scalp thus becomes one of the most important factors affecting non-invasive BCI system performance.

As shown in Fig. 3, the number of research articles dealing with the topics of non-invasive BCIs has increased dramatically in the last 30 years, as has the proportion of studies on engineering and material science and especially the development of novel electrodes for non-invasive BCIs. In this Perspective, we are primarily focused on electrode technologies for non-invasive

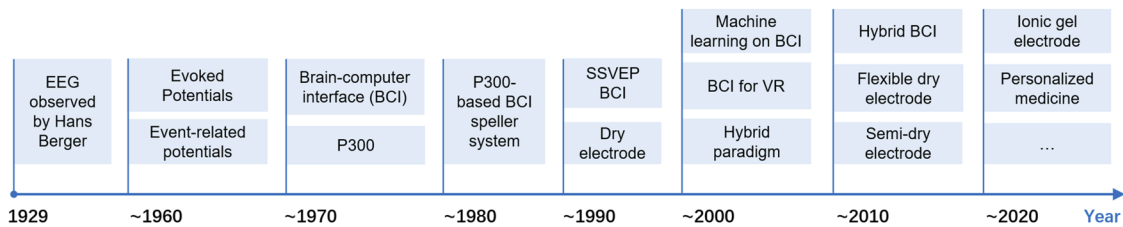


FIG. 1. Evolution of non-invasive BCI development: paradigms, electrodes, and applications.

BCIs, including their classification, evolution, functionality, range of application, security, comfort, and future development directions.

### FLEXIBLE ELECTRONICS FOR NON-INVASIVE BCIs

Practical applications of non-invasive BCIs place many requirements on electrode characteristics, such as mass manufacturing, ease of use, convenient post-processing, high conductivity, long-term stability, comfort, and, most importantly, biocompatibility and safety. In previous studies, non-invasive BCI electrodes were divided into dry and wet electrodes depending on whether the conductive gel is required. Until now, these two types of electrodes have been used in non-invasive BCI systems for EEG signal collection. Due to the high contact impedance between the electrode and the skin, dry electrodes are unsuitable for some applications that require high-quality signals and low latency. Studies have shown that the impedance of the corneum decreases significantly as humidity increases,<sup>32</sup> so pre-increasing the corneum's humidity is significant for non-invasive BCIs. In this case, commercial wet electrodes consisting of rigid Ag/AgCl disk electrodes and a cuticle infiltration agent (i.e., a conductive gel) have been proposed. Due to their corneum infiltrating ability and stable electrochemical potential, commercial wet electrodes are widely used at the present time. However, to ensure a stable connection between the electrode and the scalp, a certain amount of conductive gel must be applied at each electrode point. Such an application process is time-consuming and uncomfortable

and may even cause allergic reactions in some participants.<sup>33</sup> Cleaning up the conductive gels after each use is another complex process, during which the participant's hair follicles may be damaged. The most serious problem is that the moisture in the conductive gel evaporates continuously during the experiment, which means that once the electrode impedance has reached an acceptable value through the application of the conductive gel, a countdown begins until the gel dries. During this period, the EEG signal quality will decrease as the impedance increases until the available signal disappears altogether.<sup>34</sup>

In order to mitigate these problems, flexible non-invasive BCI electrodes have been proposed, wherein flexible dry electrodes and semi-dry electrodes are the two most representative types. The former usually consists of flexible substrate material and a conductive coating layer. In such a dry electrode BCI system, conductive gel is not required, which allows quick application without skin preparation. On the other hand, semi-dry electrodes have rapidly developed in recent years. They were optimized on the basis of both dry and wet electrodes by development of new materials and structural design. The most notable feature of semi-dry electrodes is the use of a biocompatible electrolyte, e.g., normal saline, instead of conductive gel to achieve good infiltration of the scalp cuticle. In this work, we are going to review the flexible electrode technology for noninvasive BCIs, including flexible dry electrodes and semi-dry electrodes, and propose our inductions and comments.

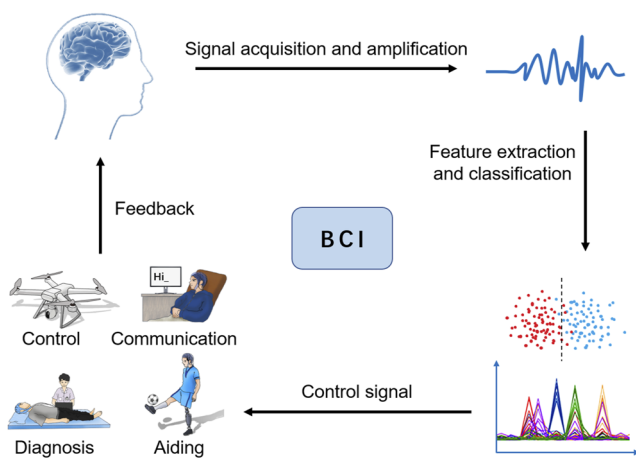
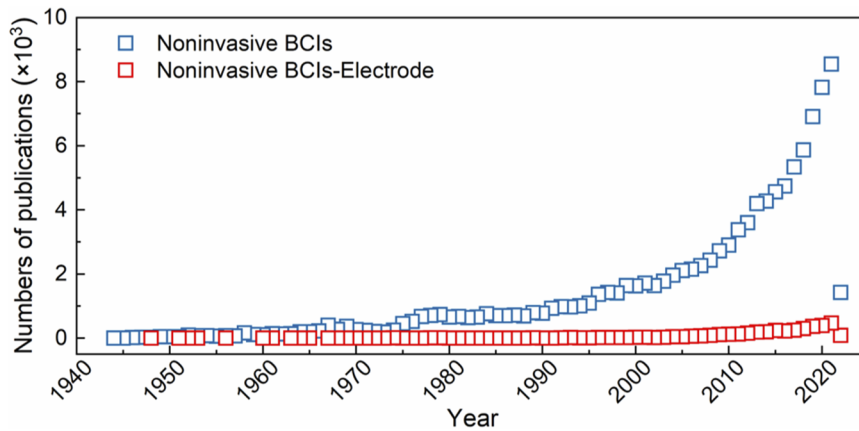


FIG. 2. Structure and functional processes of typical BCI systems.

### Flexible dry electrodes

To solve the problems of inconvenience and long-term recording instability of wet electrodes, in the 1990s, researchers presented the so-called dry electrodes, which do not require conductive gel support.<sup>35–38</sup> This type of electrode makes dry contact with the skin and has the characteristics of quick application without skin preparation, which is highly desirable for portable and wearable devices.<sup>39–42</sup> To reduce the contact impedance between the electrode and the skin, early dry electrodes are often fabricated into a sharp shape such as a pin matrix using metal or alloy materials. Because of the benefit from the rigid property and structural design, these electrodes allow direct contact to the scalp, bypassing the hair. However, the security issue is obvious. These electrodes could be dangerous to the skin due to their sharp structure and rigidity. In order to avoid these issues, flexible electrodes have been proposed. Specifically, flexible dry electrodes have been widely studied, which achieve flexibility through deformable conductors and a special variable structural design. This electrode

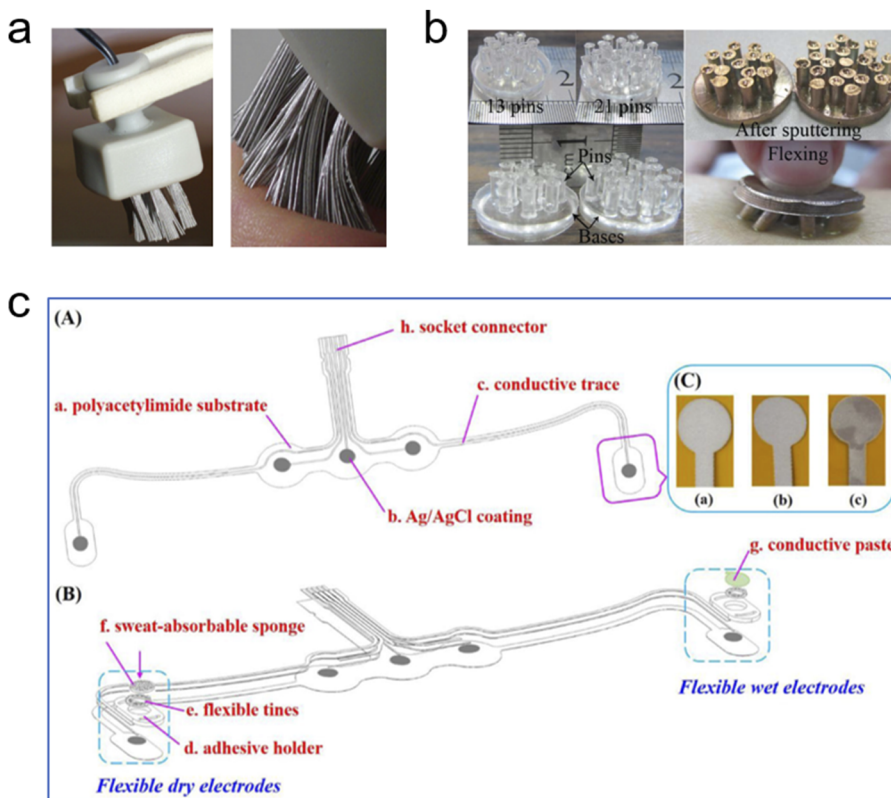


**FIG. 3.** Number of research articles published on non-invasive BCIs (blue) and non-invasive BCI electrodes (red) from 1944 to 2022. The number was obtained from the Web of Science SCI Core Collection on 2022/4/13.

achieves a good comfort level, an adequate contact area, and a practical application process due to the lack of the need for conductive gel.<sup>43,44</sup>

Grozea *et al.* proposed a new dry EEG passive electrode without signal amplification and an on-site impedance adapter, which improved existing pin-based non-invasive dry EEG electrodes.<sup>45</sup> As mentioned before, pin-based dry electrodes have unavoidable safety risks. In this work, the new passive electrode can reduce the reported discomfort by distributing the pressure on the skin of the

scalp more uniformly and more flexibly. As shown in Fig. 4(a), the new dry electrode is fabricated by flexible conductive bristles instead of rigid pins, which in the reported prototype are made of a silver-coated polymer. Wang *et al.* reported polydimethylsiloxane (PDMS) compound flexible dry electrodes for long time EEG signal acquisition [Fig. 4(b)].<sup>46</sup> Their experimental results showed that the contact impedance of the new electrodes was lower than that of a commercial wet electrode without skin preparation but higher than that with skin preparation. Considering the tedious



**FIG. 4.** Flexible dry electrodes. (a) Flexible dry electrodes consist of silver-coated polymer conductive bristles instead of rigid pins.<sup>45</sup> (b) PDMS-based flexible dry electrode sputtered with a 0.2 μm gold layer.<sup>46</sup> (c) Printable flexible Ag/AgCl dry electrode array.<sup>47</sup>

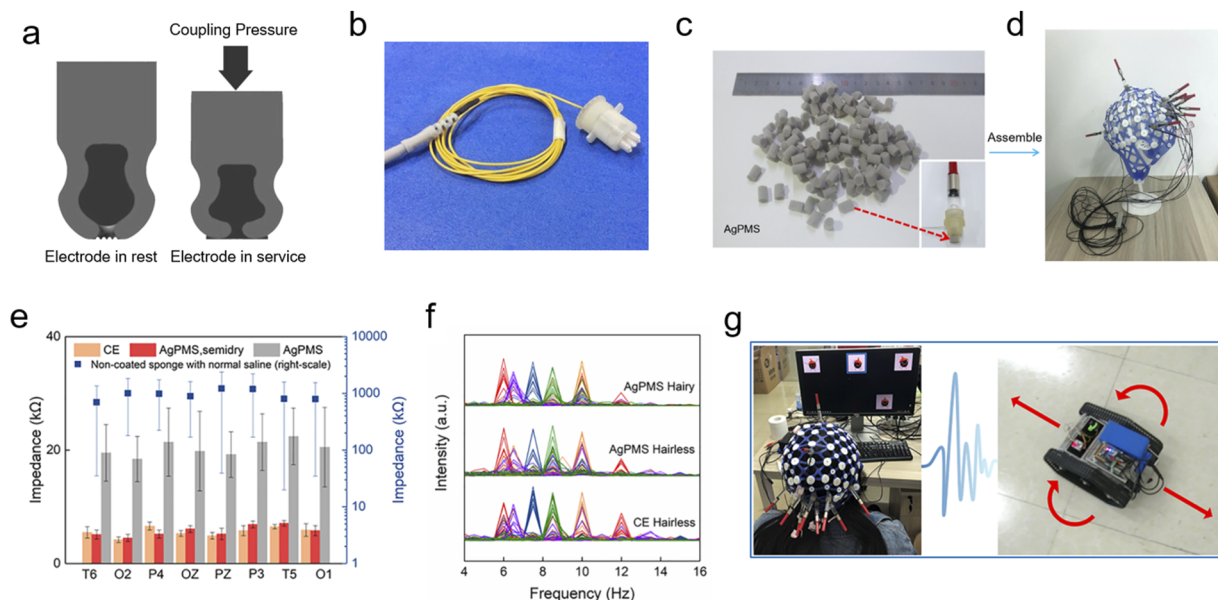
preparation process for commercial electrodes, the PDMS-based flexible electrode exhibited great practical application potential. Furthermore, such a flexible electrode contributed to fit the scalp shape for different subjects, including male and female subjects of different ages. Due to the flexible pin structure, the EEG signals collected from hairless and hairy sites using this electrode are similar to those collected using commercial wet electrodes. Li *et al.* proposed a printable Ag/AgCl dry electrode array with high flexibility, aiming at EEG signal recording [Fig. 4(c)].<sup>47</sup> The experimental results showed that the flexible dry electrode array had reproducible electrode potential, relatively low electrode–skin impedance, and good stability. Moreover, the EEG signals could be captured effectively with a quality comparable to that of wet electrodes.

### Semi-dry electrodes

Another type of flexible non-invasive BCI electrode is the semi-dry electrode, which is also known as the quasi-dry electrode.<sup>48</sup> As mentioned before, self-storage and slow release of electrolytes are two of its main characteristics different from those of dry electrodes and wet electrodes. In 2010, a hydrogel-based EEG electrode was proposed for cuticle infiltration, which could be considered as the prototype for various semi-dry electrodes reported today.<sup>49</sup> Semi-dry electrodes are important, and they have been rapidly developed in recent years. Semi-dry electrodes are also fabricated by flexible materials or special structures such as elastomers and spring structures such as flexible dry electrodes. The difference is that

semi-dry electrodes will not require and release as many electrolytes as wet electrodes due to their special water storage structure and material, for example, porous sponge and hydrogel. This characteristic allows semi-dry electrodes to eliminate short circuit interference between electrodes and maintain relatively low contact impedance. Moreover, semi-dry electrodes have a high comfort level due to the Young's modulus matching between the electrode materials and the human scalp. Therefore, semi-dry electrodes are more suitable for long term applications such as sleep monitoring and rehabilitation therapy.

In 2013, Mota *et al.* first proposed the concept of semi-dry electrodes. Their semi-dry electrode was able to expel 30  $\mu\text{l}$  of a hydrating agent as a substitute for commercial conductive gel. Therefore, the semi-dry electrode can substantially reduce the use of commercial conductive gel and achieve a satisfactory contact impedance for non-invasive BCI systems [Fig. 5(a)]. Duan's group reported a passive semi-dry electrode based on porous ceramic pillars for non-invasive BCIs [Fig. 5(b)]. Their electrode was able to release a small dose of electrolytes, saline solution, with the assistance of capillary force through porous ceramic pillars. As a result, stable contact impedance between the electrode and the scalp was obtained. Moreover, the variation in contact impedances between nine different positions was less than 5 k $\Omega$ , indicating a high uniformity for such a semi-dry electrode. In 2019, our group reported a flexible silver-nanowire/polyvinyl butyral/melamine sponge, the so called AgPMS, semi-dry electrode for non-invasive BCIs on hairless and hairy scalps [Figs. 5(c) and 5(d)].<sup>50</sup> Benefitting from the porous structure of the sponge and the high conductivity of



**FIG. 5.** Semi-dry electrodes. (a) Schematic diagram of a semi-dry electrode expelling 30  $\mu\text{l}$  of the hydrating agent.<sup>48</sup> (b) Photograph of a passive semi-dry electrode based on porous ceramic pillars.<sup>49</sup> (c) More than 100 AgPMSs were prepared using vacuum infiltration processing. The inset shows the designed hollow cylinder electrode, consisting of a PVC shell, infiltrated normal saline, and an AgPMS contact.<sup>50</sup> (d) EEG cap with 10 integrated electrodes, where 8 AgPMS electrodes are located at the T5, P3, PZ, P4, T6, O1, OZ, and O2 sites.<sup>50</sup> (e) Contact impedance on different channels between electrodes and the skin.<sup>50</sup> (f) Power spectrum extracted from 50 trials of SSVEP measurements using conventional electrodes and AgPMS semi-dry electrodes on hairless and hairy skin.<sup>50</sup> (g) EEG signal-recording and instruction-mapping experiment: mind-control of a driverless car using an AgPMS semi-dry electrode BCI system on hairy skin.<sup>50</sup>

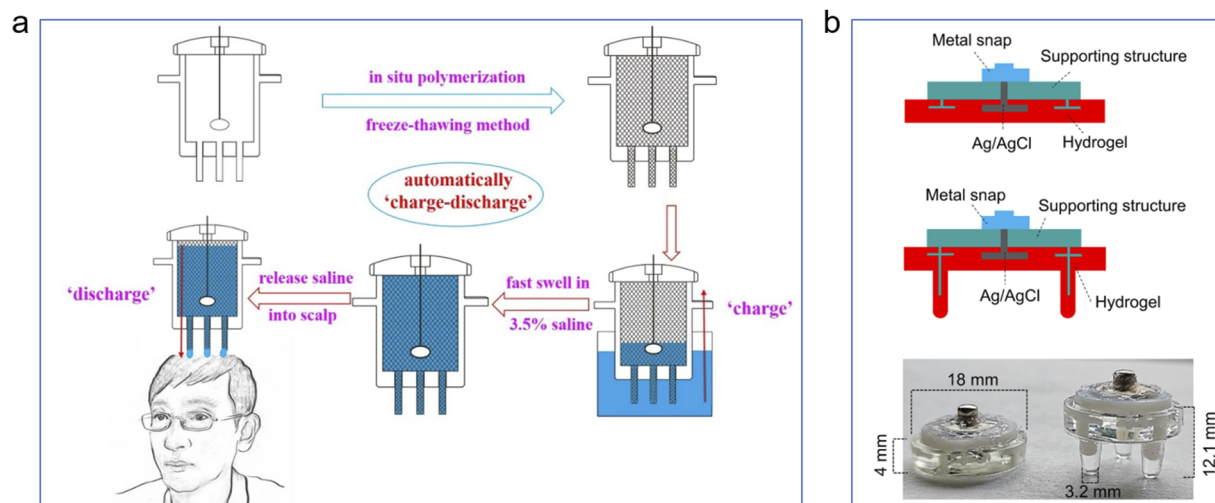
AgNWs, the new electrode exhibits good electrolyte storage capacity, high flexibility, and low contact impedance, which enables stable EEG signal recording on both hairless and hairy scalps [Figs. 5(e) and 5(f)]. Moreover, we demonstrated a mind-control experiment of a driverless model car by a hairy subject [Fig. 5(g)], which verified that such a new semi-dry electrode can improve the performance of gel-free non-invasive BCIs and is suitable, for example, for assistive devices for the disabled as well as EEG recording for the diagnosis of neural disorders and monitoring of mental states.

Hydrogels are considered one of the most promising bioelectronic materials because their soft and flexible nature allows minimization of the mechanical mismatch with biological tissues while their high water content provides wet and ion-rich physiological environments.<sup>51</sup> Hydrogel EEG electrodes for preparation-free non-invasive BCI systems were first proposed by Alba *et al.* in 2010.<sup>52</sup> In their work, the as-prepared hydrogel electrode exhibited 99.2% of ID water or 91% of electrolyte solution storage capacity due to its super-absorbent hydrogel component. For long-term experiments, the hydrogel electrode could maintain low contact impedance over 8 h. Li *et al.* proposed a super-porous hydrogel-based semi-dry EEG electrode, enabling an automatically “charged–discharged” electrolyte to form a low and stable electrode–scalp impedance [Fig. 6(a)].<sup>53</sup> Shen *et al.* reported a flexible hydrogel electrode with a strong moisturizing ability for long-term EEG recording [Fig. 6(b)].<sup>54</sup> In their work, the hydrogel was synthesized by polymerizing the N-acryloyl glycinamide monomer, wherein a certain amount of glycerin and kalium chloratum was added to the hydrogel to increase its moisture retention and electrical conductivity, respectively. Recently, our group proposed a flexible, cost-effective, mass-producible, highly robust, controlled-released electrolyte silver-nanowire/polyvinyl alcohol hydrogel/melamine sponge, the so called AgPHMS, semi-dry electrode for preparation-free long-term non-invasive BCI systems [Fig. 7(a)].<sup>55</sup> The

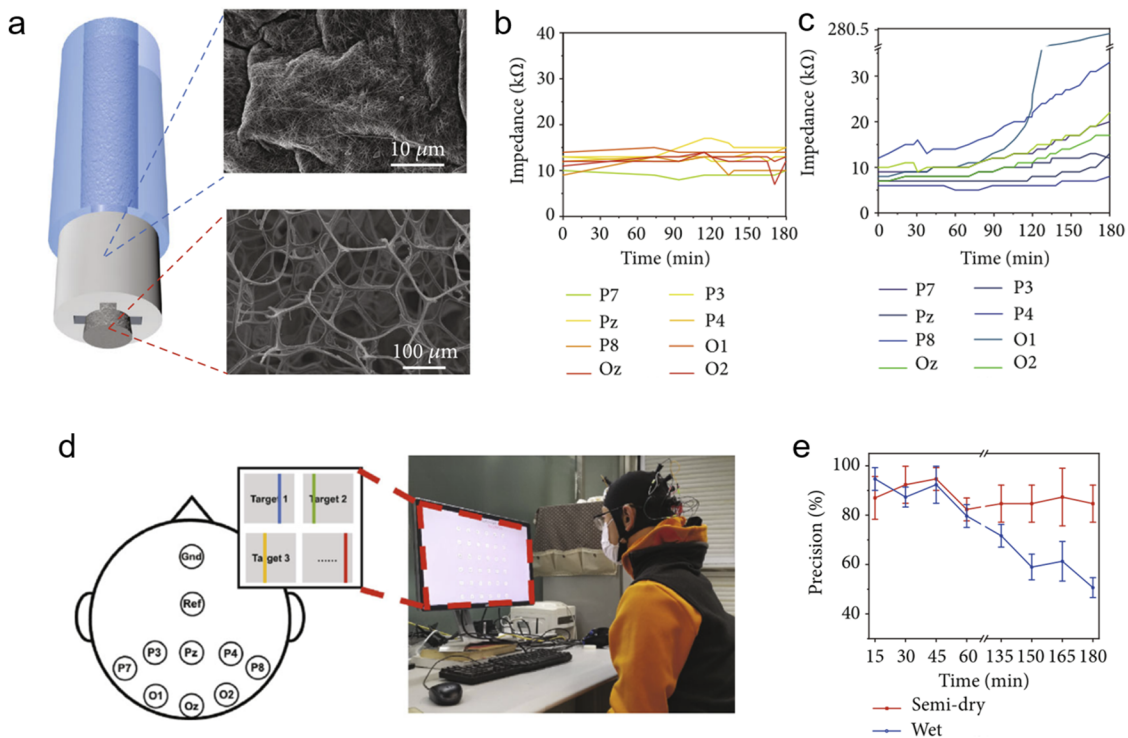
electrolyte solution in the hydrogel electrode could be slowly released to a fixed point without any special liquid storage or external transport structure. Experimental results showed that such a slowly releasing mechanism of the electrolyte by the hydrogel–sponge hybrid can increase the long-term stability of the whole electrode [Figs. 7(b) and 7(c)]. In our work, the mVEP experiments showed a 77%–100% accuracy for the AgPHMS semi-dry electrodes, and this high accuracy could be maintained for more than 3 h [Figs. 7(d) and 7(e)].

## CONCLUSION AND FUTURE PERSPECTIVE

With the continuous development of materials science, flexible electronics, integrated circuits, chip technology, and computer science, we are fortunate in witnessing the rapid evolution of BCIs.<sup>56–59</sup> At the present time, invasive and non-invasive BCI technologies are being developed in parallel, aiming at their respective goals, where invasive BCIs are focused on solving cutting-edge problems in brain science, biomedicine, and neuroscience,<sup>60–62</sup> while non-invasive BCIs exhibit extremely broad commercial application scenarios, including communication,<sup>63,64</sup> disease diagnosis and treatment,<sup>65</sup> daily tasks,<sup>66–68</sup> emotion detection,<sup>69,70</sup> and virtual reality.<sup>71–73</sup> By continuously improving the safety, comfort, portability, long-term operation ability, and signal analysis methods, non-invasive BCI technology is likely to take a huge leap forward in medical knowledge and even revolutionize the way we live. For hardware, all-flexible and highly portable BCI systems are highly desirable and constitute a recognized direction of development, which relies on interdisciplinary development such as materials science and flexible electronics.<sup>74–79</sup> Semi-dry electrodes are an important field for non-invasive BCI technology due to their usability, low contact impedance, and good biosecurity. The future directions of semi-dry electrodes may include (i) development of novel ionic gels for higher conductivity, (ii) design of



**FIG. 6.** Hydrogel-based semi-dry electrodes. (a) Schematic diagram of the working principle of super-porous hydrogel-based semi-dry electrodes.<sup>53</sup> (b) Schematic diagram and photographs of planar and columnar hydrogel electrodes.<sup>54</sup>



**FIG. 7.** Semi-dry electrode consists of polymer sponge, hydrogel, and silver nanowires.<sup>55</sup> (a) Illustration of the structure of the AgPHMS semi-dry electrode and local SEM images. (b) Impedance of the AgPHMS semi-dry electrode system on different channels. (c) Impedance of a commercial wet electrode system on different channels. (d) Brain mapping using an AgPHMS semi-dry electrode EEG cap in a BCI system and typing using mVEP mapping. (e) Accuracy of typing during the first and third hours using the AgPHMS semi-dry electrode and a commercial wet electrode.

special structures for precise and slow release of electrolytes, aiming to further extend the minimum operation time of BCIs, and (iii) lightweight designs and Young’s modulus matching for improving comfort levels.

New forms of non-invasive BCIs are another development direction, aiming to achieve the ability to perform more complex tasks. For collaborative tasks, cooperative BCIs can be built, allowing multiple subjects to implement tasks cooperatively and simultaneously.<sup>80–82</sup> Synchronized acquisition and real-time analysis of EEG information from multiple subjects are feasible, thanks to the ease of use of flexible non-invasive BCIs. In addition, convenience and comfort features of flexible electrodes enable rapid development of hybrid BCIs (hBCIs). In hBCI systems, multimodal biological signals are collected and used in combination in order to improve the recognition rate of systems using only single-mode EEGs.<sup>83,84</sup> This can further help develop novel high-flux BCI loops for complex task processing. Moreover, hBCIs also exhibit important implications for biomedicine as they may be able to promote research on the synergistic mechanisms between the brain and the peripheral nerves.

In conclusion, we provide a brief review on flexible electrode technologies for non-invasive BCIs, including two types of the most representative flexible electrodes: dry electrodes and semi-dry electrodes. The summary of the features and the comparison

between commercial wet electrodes and flexible electrodes are intuitively shown in Tables I and II. Further intensive and interdisciplinary research on non-invasive BCIs is required to overcome the barrier between experimental research and practical application. With deeper investigation of material properties, structural design, manufacturing methods, and improvements of biocompatibility and usability, flexible electrode based non-invasive BCIs will be able to satisfy the requirements of broader applications.

**TABLE I.** Comparison between wet electrodes, flexible dry electrodes, and semi-dry electrodes.

	Wet electrodes	Flexible dry electrodes	Semi-dry electrodes
Manufacturing scalability	Good <sup>33</sup>	Good <sup>56</sup>	Medium <sup>38</sup>
Easy to use			
(rapid and convenient setup)	No <sup>57,58</sup>	Yes <sup>56,59</sup>	Yes <sup>58</sup>
Comfort level	Low <sup>57</sup>	High <sup>56,59</sup>	High <sup>58</sup>
Contact impedance	Low <sup>57</sup>	High <sup>50</sup>	Low <sup>58</sup>
Long-term stability <sup>58</sup>			
(impedance variation)	Bad <sup>50</sup>	Medium <sup>44</sup>	Good <sup>55</sup>
Biocompatibility	Medium <sup>57</sup>	Good <sup>59</sup>	Good <sup>57</sup>

**TABLE II.** Advantages and disadvantages of wet electrodes, flexible dry electrodes, and semi-dry electrodes.

	Wet electrodes	Flexible dry electrodes	Semi-dry electrodes
Advantage	Electric potential reproducibility, excellent signal to noise ratio, reliability, and manufacturing scalability. <sup>48</sup>	Quick application without skin preparation, which is highly desirable for portable and wearable devices. <sup>39–42</sup>	Gel-free; does not release as many electrolytes as wet electrodes due to their special water storage structure and material, which allows semi-dry electrodes to eliminate short circuit interference between electrodes and maintain relatively low contact impedance. <sup>55</sup> Semi-dry electrodes have a high comfort level due to the Young's modulus matching between the electrode materials and the human scalp. <sup>50</sup>
Disadvantages	Applying the conductive gels is time-consuming and uncomfortable and may even cause allergic reactions in some participants. <sup>32</sup> Cleaning up the conductive gels after each use is another complex process, during which the participant's hair follicles may be damaged. When the conductive gels are drying, the EEG signal quality will decrease as the impedance increases until the available signal disappears altogether. <sup>34</sup>	Bulkier, more expensive, and more susceptible to movement artifacts due to the absence of a liquid contact. <sup>48</sup>	The requirement of special materials and structural design limits their large-scale manufacture.

## ACKNOWLEDGMENTS

This study was supported by the National Natural Science Foundation of China (Grant No. 62104051) and the National Basic Research of China (Grant No. 2018YFB0104404).

## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

## Author Contributions

**Zhibao Huang:** Data curation (equal); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). **Zenan Zhou:** Data curation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Jiasheng Zeng:** Writing – original draft (equal); Writing – review & editing (equal). **Sen Lin:** Conceptualization (lead); Data curation (equal); Funding acquisition (lead); Resources (lead); Supervision (lead); Visualization (lead); Writing – original draft (equal); Writing – review & editing (equal). **Hui Wu:** Conceptualization (equal); Funding acquisition (equal); Methodology (equal); Supervision (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (lead).

## DATA AVAILABILITY

Data available on request from the authors.

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