Editorial

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Are artificial retinas merely an approach to recover sight, or are they a tool of augmented reality beyond natural eyes in blind people?

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SUMMARY: Implantable artificial retinas have been a considerable technology to help blind people recover their sight. This topic has attracted increasing attention from both patients and clinicians because of the refractory nature of degenerative retinal diseases. A point worth noting is that artificial retinas are conventionally considered to be a tool to help blind patients recover their sight. With the development of materials and sensors, however, such devices might have characteristics of augmented reality that are beyond the capabilities of the natural eye. This study briefly summarizes the current clinical status of implantable artificial retinas, it explores emerging technologies that aim to augment vision, and it discusses the challenges that must be overcome before these devices can be further used clinically. Indeed, the implantation of such advanced retinal prostheses with augmented reality characteristics may bring about new ethical and legal risks that warrant further consideration.

Keywords: degenerative retinal diseases, artificial retina, augmented reality, blind, retinal prosthesis

1. Background

Degenerative retinal diseases, such as retinitis pigmentosa and age-related macular degeneration (AMD), may cause irreversible loss of photoreceptors; however, inner retinal neurons and optic nerve pathways are commonly preserved (*1,2*). Although next-generation therapies, such as gene therapy (*3*), stem cell transplantation (*4*), and pharmacological interventions, have yielded promising results for specific etiologies, late-stage degeneration remains refractory and lacks efficient treatment. Accordingly, implantable artificial retinas, or retinal prostheses, which represent a compelling technological pathway to restore partial vision by bypassing the damaged photoreceptor layer and electrically stimulating the remaining neural circuits of the retina, have been considered (*5*). Over the last two decades, these devices have developed from laboratory prototypes to clinically tested implants, which contribute to light perception, motion detection, and basic object recognition in blind patients (*6-8*) (Table 1). However, the field is undergoing a conceptual shift: the next generation of artificial retinas may not only restore lost sight but also improve visual perception beyond the natural human spectrum with development of the computerized technology such as artificial intelligence (*5*) and sensors (*9*). This topic has attracted increasing attention from both patients and clinicians. Therefore, the current study briefly summarizes the current clinical status of implantable artificial retinas, it explores emerging technologies that aim to augment vision, and it discusses the challenges that must be overcome before these devices can be further used clinically.

2. Status of clinical study

All retinal prostheses follow a common principle, that is, the conversion of optical stimuli into electrical impulses, thereby directly activating residual retinal neurons or the optic nerve (*10*) (Figure 1A). In terms of their clinical study, current retinal prosthesis systems mainly differ in the implantation site and mechanism of stimulation as exemplified by the epiretinal Argus II (*11*), subretinal Alpha AMS/IMS (*6,8*) and PRIMA (*4,12*), and suprachoroidal 44-channel implants (*13*), the surgical accessibility, signal fidelity, and long-term stability of which are being considered in human beings. Clinical trials of these major retinal prostheses have consistently demonstrated partial restoration of light perception, object localization, and basic motion detection in patients

Table 1. Major artificial retina devices

Device/Study	Characters	Strengths	Weakness	Comments
Human				
PRIMA Holz *et al.* 2025 (*14*)	Wireless photovoltaic subretinal implant using near-IR light for activation	Self-powered; compact; achieved letter recognition under IR light	Limited field of view; requires external IR projection	Clinical phase II trial ongoing. The milestone marked the transition of artificial retina technology into the clinically applicable stage
A 44-Channel electrode Allen *et al.* 2025 (*13*)	Suprachoroidal electrode array with 44 stimulation channels for safer surgical implantation	Stable operation >2 years; minimal adverse events; low surgical risk	Limited resolution and brightness perception	Human trials ongoing. Highlights a safety-first direction in artificial retina development and provides a new pathway that balances safety and restoration of function
Alpha AMS Edwards *et al.* 2018 (*8*)	Subretinal 1600-pixel photodiode array with integrated amplifiers	Improved spatial resolution and object recognition	Requires external camera and cable link; limited field of view	Regulatory approval received. Marked a shift in subretinal prosthesis technology from experimental proof-of-concept to sustainable clinical use, breaking free of the constraints of external imaging systems.
Argus II da Cruz *et al.* 2016 (*7*)	Epiretinal 60-electrode system with external camera and processor	Partial restoration of light perception, motion, and orientation	Low visual acuity (>2 logMAR); high rehabilitation demand	Regulatory approval received. Provided valuable experience for the subsequent validation of prosthetic safety and durability
Alpha IMS Stingl *et al.* 2013 (*18*)	Early version of subretinal microphotodiode implant	Restored letter recognition and shape discrimination	Complex surgery; limited durability	Regulatory approval received, early attempts at artificial retina development
Animal				
Tellurium nanowire retinal nanoprosthesis Wang *et al.* 2025 (*9*)	Nanowire array implant converting NIR and visible light into electrical signals	Enabled both restoration of vision and infrared perception in animal models	Long-term biocompatibility under evaluation	Landmark study for "superhuman" infrared vision
POLYRETINA Vagni *et al.* 2025 (*24*)	Flexible titanium-based electrode arrays that convert light directly into stimulation currents	Achieved wireless, large-area stimulation and a wide field of view *via* foldable injectable implantation.	Only short-term safety and function verified; long-term stability unassessed.	Paved the way for the future wireless, minimally invasive, and wide-field artificial vision technologies
AuTiO_2-xNW arrays Yang *et al.* 2024 (*21*)	Heterostructure nanowire array with a high level of photoresponsivity	Broad spectral range; low operating voltage	Complex fabrication process	The first step in translating nanoscale photoelectric conversion into the context of primate vision
Liquid-metal-based 3D microelectrode arrays integrated with ultrathin Chung *et al.* 2023 (*25*)	Stretchable 3D liquid-metal microelectrodes for conformal neural stimulation	Excellent flexibility and durability; strong retinal adhesion	Requires further miniaturization; early preclinical stage	Promising for chronic soft implants
Plasmonic gold nanorods (AuNRs) Nie *et al.* 2022 (*28*)	Plasmonic nanoparticles that convert light into localized electric fields	High photothermal efficiency; minimally invasive	Limited control over spatial stimulation; short-term effect	Proof-of-concept stage

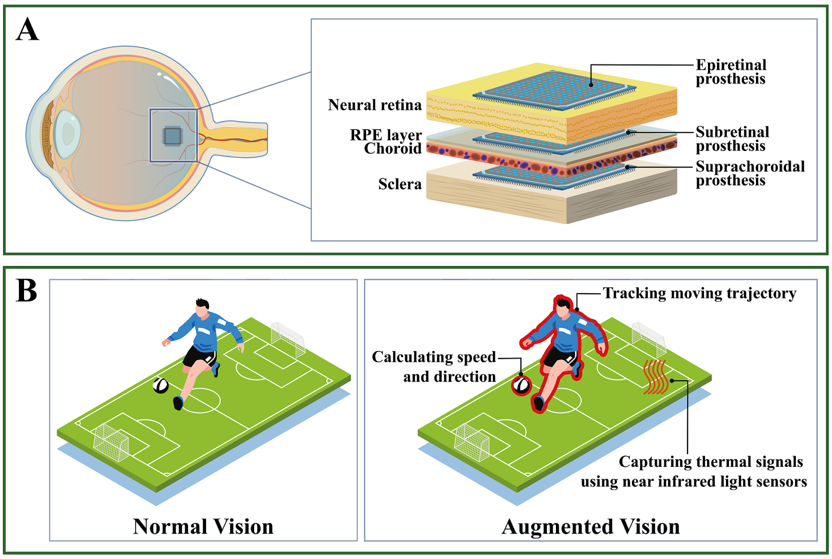

Figure 1. Diagrams of an artificial retina. (A). Diagram of the principle behind an artificial retina. **(B)**. The future of artificial retinas and the capability of augmented reality in artificial retinas beyond natural eyes, *i.e.*, the concept of "superhuman vision". RPE, retinal pigment epithelium.

with end-stage retinal degeneration, with acceptable safety and multiyear stability outcomes. Currently, several studies have documented significant progress in this field. Holz *et al*. reported that subretinal implantation of the PRIMA device in patients with AMD successfully restored central vision (*14*). Allen *et al*. demonstrated that implantation of a 44-channel suprachoroidal device did not result in severe adverse events during 2.0–2.7 years of follow-up (*13*). However, the level of restored vision remains rudimentary, and extensive rehabilitation is commonly required for functional adaptation (*15*). Nevertheless, evidence regarding safety, stability, and neural plasticity provides a solid clinical working basis for further innovation in visual prosthetics (Table 1).

Based on the technologies available thus far, development of retinal prostheses for patients still faces several interrelated challenges. The most fundamental limitation lies in the restricted number and spacing of stimulating electrodes, which spread an electrical charge within the neural tissue that diffuses the area of stimulation and results in a constraint on spatial resolution (*16*). Advances in microfabrication using novel materials such as graphene, flexible polymers, and liquid metal arrays may improve precision, but injection safety and biocompatibility must be considered (*17*). Biological integration also remains problematic; fibrotic encapsulation, gliosis, and immune responses can degrade electrode–tissue interfaces, whereas long-term implants often show increased impedance and reduced current efficiency (*18,19*). To address this issue, future designs must employ soft biomimetic materials that conform to the retinal curvature and exhibit mechanical compliance. Power delivery is another challenge because conventional trans-scleral cables or inductive coils are not satisfactory for device miniaturization and patient comfort (*20*). Novel approaches, including near-infrared (NIR) laser-driven wireless powering and photovoltaic energy harvesting, are emerging technologies for fully implantable systems that eliminate external wiring and reduce the burden of surgery (*12,21*). Finally, even when light perception is restored, patients' subjective visual experience varies widely and is impacted by the residual neural architecture, cortical adaptability, and duration of blindness. Accordingly, individualized rehabilitation, which integrates virtual reality training and neural feedback, is commonly required to enhance perceptual adaptation and optimize functional outcomes (*22*).

3. Status of preclinical studies

Emerging retinal prosthesis technologies are being developed to provide sophisticated, efficient, and biologically integrated solutions. Many novel devices or materials have been verified in preclinical studies. Photovoltaic and self-powered systems, such as the POLYRETINA implant, use titanium electrodes to convert light directly into stimulation currents, thus eliminating the need for bulky external power supplies and resulting in functional letter recognition under infrared illumination in clinical settings (*23*). A later study verified the efficacy of the POLYRETINA device in a chemically-induced blindness minipig model (*24*). Results indicated that the POLYRETINA device helped to restore light responses in blind minipigs. Chung *et al*. described a novel soft liquid-metal-based three-dimensional microelectrode that offered the advantage of reducing the impedance of the stimulation electrodes (*25*). The novel liquid-metal material showed satisfactory proximity to the retinal ganglion cells in blind mice, thereby minimizing damage to the retina. Moreover, it can provide effective charge injections. The advantages of this novel liquid-metal-based microelectrode were verified in blind mouse models. Recently, Wang *et al*. described a tellurium-nanowire nanoprosthesis that not only restored visual function but also enabled the perception of near-infrared wavelengths, thereby extending vision beyond the normal spectral range in blind mice (*9*). These innovations have realized the dual restorative and augmentative potential of photovoltaic nanostructures. At the same time, advances in flexible and bio-integrative electronics have enhanced device-tissue compatibility. Polymer-based microelectrode arrays conform closely to the retinal curvature, improve mechanical stability, and minimize inflammatory responses (*24*), whereas stretchable optoelectronic synapses with broadband sensitivity and neuromorphic plasticity achieve a balance between optical sensing and neural computation (*26*), enabling adaptive learning prostheses that co-evolve with neural tissue. Finally, recent advances in nanotechnology offer new possibilities for retinal prosthesis implantation beyond conventional approaches. Instead of requiring the complex surgical placement of electrode arrays, tunable NIR nanoparticle sensors and plasmonic nanorods can be directly implanted into the eye *via* minimally invasive intravitreal injection, as has been done in blind rats (*27*) and mice (*28*). This less invasive and simplified surgical strategy helps to reduce procedural complexity and reduce the incidence of long-term complications. Moreover, it can offer compatibility with future electronic or optogenetic interfaces, higher spatial resolution, and lower stimulation thresholds, thus improving functional outcomes. These preclinical studies presage a bright tomorrow for implantable artificial retinas, and their future clinical applications are eagerly anticipated.

Beyond the sole aim of vision restoration, the next generation of retinal prostheses might have the potential to enhance and extend human visual perception (*26,27*). Human vision is limited to approximately 380–750 nm, where retinal photoreceptors (rods and cones) absorb light most efficiently through opsin-mediated phototransduction. Longer wavelengths carry too little photon energy to trigger the conformational changes needed for visual signaling, whereas shorter wavelengths, although energetic, are largely absorbed by the cornea and lens and can damage photopigments, thereby reducing effective vision. Emerging technologies and materials might enable artificial retinas to transcend natural limitations and evolve into a platform for sensory augmentation (*26,27*). For instance, biomimetic nanocluster photoreceptors can detect circularly polarized light, mimicking the polarization vision of crustaceans, thereby enabling improved edge detection and contrast sensitivity beyond the capabilities of the human eye (*29*). Tellurium-nanowire nanoprostheses and retinomorphic devices are sensitive to near-infrared wavelengths of approximately 980 nm, thus illustrating the feasibility of integrating infrared perception into visual systems (*10,30*). Further advances in quantum dot and perovskite materials have the potential for hyperspectral and multimodal sensing, allowing discrimination across a far broader range of wavelengths than the trichromatic human retina (*31*).

4. Concluding remarks: How to bridge the gap between the bench and bedside?

With the development of material science, neural engineering, and computational neuroscience, novel devices and suprachoroidal implants are emerging. Relying on the reconstruction of adaptive feedback loops and in-sensor processing, dynamic process stimulations, such as ambient light, gaze, or cognitive intent can be expected. In this regard, future artificial retinas can be considered not only as therapeutic tools but also as neural enhancement interfaces, offering expanded spectral awareness, adaptive contrast tuning, and context-dependent optimization (Figure 1B). At the same time, these characteristics may be beneficial for improving navigation under low-light conditions, enhancing surgical precision, and serving as experimental platforms for cognitive amelioration in a clinical setting.

However, the actual state of clinical verification thus far is that most of the clinical trials involving artificial retinas focus on recovery of primary vision. There is still a long way to go before the advanced materials and sensors mentioned earlier can be actually be used clinically. In addition to technological factors, several problems must be addressed before clinical use. *i)* An advanced assessment system that is applicable to novel artificial retinas should be devised. *ii)* A comprehensive understanding of traditional assessments, such as standardized visual performance assessments and cortical activity mapping, must be achieved to obtain comparable, unbiased, and reproducible results (*32*). *iii)* Personalized visual training and rehabilitation protocols are required. In addition, the potential for sensory enhancement in healthy individuals may pose complex societal challenges that must be addressed (*33*). *iv*) Implantation of such advanced retinal prostheses with augmented reality characteristics may bring about new ethical and legal risks. The main risk relates to the potential for "superhuman vision," with protheses that surpass medical aids and that have more functions beyond those of normal human eyes. The primary aim of implantation of artificial retinas is to help blind patients "see again," so is such "superhuman vision" really necessary for the blind? Such superhuman vision aided by artificial intelligence may lead to a "superman," but that might be considered "unfair" to normal people in whom artificial retinas have not been implanted. Indeed, the potential to have "superhuman vision" is appealing.

Thus, implantation of artificial retinas might be abused by, for example, a normal person who need not undergo that surgery. In addition, preventing such "superhuman vision" from been used for illegal purposes is also a problem. These issues require further investigation.

In conclusion, this study briefly summarized the current status of artificial retinas in terms of clinical studies, devices, and materials. Although the clinical use of artificial retinas remains limited so far, this study described promising scenarios for their use based on the development of computerized and material technologies. However, ethical issues regarding "superhuman vision" should be considered before such novel devices are actually used in clinical practice. Looking solely from the viewpoint of technology, however, such "superhuman vision" might profoundly impact not only ophthalmology but also the fields of neuroscience and cognitive science (*34*), rehabilitation (*35*) and ethics since the recovery of senses (vision, hearing, *etc*.,) helps to restore cognitive function and facilitate rehabilitation, both of which are often impacted by impaired senses (*34,35*).

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