

Asia Pacific Journal of Clinical Medical Research

Editor-in-Chief:

Assoc. Prof. Danying Liao

Tongji Medical College, Huazhong University of Science and Technology, China

Copyright © 2025. ASIA PACIFIC SCIENCE PUBLICATIONS
COMPANY LIMITED. Complimentary Copy.

Asia Pacific Journal of Clinical Medical Research

Asia Pacific Journal of Clinical Medical Research (APJCMR) is an international, peer-reviewed, open access journal dedicated to advancing clinical medical research across multiple disciplines. The journal serves as a platform for publishing high-quality original research, reviews, and clinical studies that enhance the understanding of medical practices, treatment innovations, and healthcare outcomes, thereby supporting patient care and medical advancements in the Asia Pacific region and beyond. It covers mainly but not limits to the following areas:

- Advancements in Clinical Practice and Patient Care
- Evidence-Based Medicine
- Healthcare Outcomes and Treatment Efficacy
- Patient Safety and Harm Reduction
- Medical Ethics and Clinical Decision-Making
- Clinical Trials and Medical Interventions
- Healthcare Policy and Management
- Public Health and Preventive Medicine
- Medical Education and Training
- Innovations in Medical Technologies
- Special Medical Fields and Rare Diseases
- Healthcare Systems and Organizational Studies

About Publisher:

Asia Pacific Science Press (APSP) is a swiftly expanding publisher of peer-reviewed and open-access journals, strategically located in Hong Kong. As a reliable and esteemed corporation, APSP is dedicated to promoting and serving a wide array of subject areas, ultimately contributing to the betterment of humanity. By disseminating knowledge to a global community of scholars, practitioners, researchers, and students, we strive to establish ourselves as the world's leading independent academic and professional publisher.

Submission instructions: You can submit your manuscript through the official website (www.apspublisher.com) or email (editor.chst@apspublisher.com). All manuscripts will go through a rapid peer review and production, making the process of publishing simpler and more efficient.

Publisher Headquarter

Room 03, 7th Floor, Block B, Tuen Mun Industrial Centre, 2 New Ping Street, Tuen Mun, Hong Kong, China
Website : www.apspublisher.com
Email : www.apspublisher.com

Fujian Province Office, China

603-1, 6th Floor, Building B20, Chengyi North Street, Software Park, Jimei District, Xiamen City, Fujian Province, China
Website : <https://ojs.apspublisher.com/index.php/amit>
Email : amit@apspublisher.com

Table of Contents

- 1 Perspectives on Transcranial Direct Current Stimulation (tDCS) and Its Potential Integration With Nuclear Medicine as a Therapeutic Approach**
Suman Pradhan, Subhasish Chatterjee, Mousumi Saha
- 5 Home Accessibility Renovation for Households with Disabilities in China: International Practices and Policy Implications**
Jin Chen, Hailang Liu, Jingru Shan, Zhenkun Xu
- 15 The Role and Mechanism of Acupuncture Analgesia in the US Opioid Crisis Research**
Tingting Zhu, Chengbo Zhen
- 24 A Review of Postoperative Outcomes and Complication Management in Cataract Surgery**
DengFeng Wang
- 37 Short Communication - A Comparative Physiological and Technical Evaluation of Skull Micro-Movement Detection Using Dual Mechanical Actuators and Flat Eddy-Current Sensor Systems: Toward a Standardized Framework for Cranial Micro-Oscillation Measurement in Humans**
Suman Pradhan, Subhasish Chatterjee

Perspectives on Transcranial Direct Current Stimulation (tDCS) and Its Potential Integration With Nuclear Medicine as a Therapeutic Approach

Suman Pradhan, Subhasish Chatterjee*, Mousumi Saha

Maharishi Markandeshwar Institute of Physiotherapy & Rehabilitation, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana, India

**Corresponding author: Subhasish Chatterjee, subhasishphysio@mmumullana.org*

Copyright: 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY-NC 4.0), permitting distribution and reproduction in any medium, provided the original author and source are credited, and explicitly prohibiting its use for commercial purposes.

Abstract: Transcranial direct current stimulation (tDCS) is a non-invasive technique that modifies cortical excitability and induces neuroplasticity using low-intensity electrical currents. Nuclear medicine technologies like positron emission tomography (PET) and single-photon emission computed tomography (SPECT) can quantify cerebral metabolism and other dynamics. Evidence suggests that combining tDCS with these imaging methods enhances understanding and outcomes for neurological and psychiatric conditions. This review highlights how nuclear medicine can objectively characterize tDCS effects, map network modulation, and identify predictive biomarkers. PET and SPECT indicate changes in glucose metabolism and neurotransmitter activity post-tDCS, demonstrating their value in validation. While the co-application of these methodologies is still in conceptual stages, their integration may advance precision neuromodulation and inform rehabilitation strategies.

Keywords: Depression; Nuclear Medicine; Transcranial Direct Current Stimulation; Cortical Excitability; Neuronal Plasticity; Tomography

Published: Jan 16, 2026

DOI: <https://doi.org/10.62177/apjcmr.v2i1.1025>

1.Introduction

Transcranial direct current stimulation (tDCS) has emerged over the past two decades as a non-invasive neuromodulation technique capable of altering cortical excitability and inducing neuroplastic changes through the application of weak, constant electrical currents to the scalp. Originally conceptualized in electrophysiological research, tDCS has since expanded into clinical neuroscience, rehabilitation, psychiatry, and cognitive enhancement, largely due to its safety, portability, and steadily accumulating evidence of therapeutic potential. The technique primarily operates by modulating neuronal membrane potentials like anodal stimulation promotes depolarization and increased excitability, whereas cathodal stimulation generally produces hyperpolarization and reduced excitability (Lang et al., 2005). These effects interact with synaptic plasticity mechanisms, including NMDA receptor-dependent pathways, long-term potentiation (LTP), long-term depression (LTD), and changes in neurotransmitter systems such as glutamate and GABA. In parallel, nuclear medicine has advanced considerably in its ability to quantify functional and molecular brain processes through imaging modalities such as positron emission tomography (PET) and single-photon emission computed tomography (SPECT) (Kwon & Jang, 2011). These tools allow

investigators to observe cerebral glucose metabolism, neurotransmitter receptor activity, neuroinflammation, regional cerebral blood flow, and neurodegenerative protein deposition with remarkable sensitivity. As personalized medicine and precision neurotherapeutics evolve, a compelling question arises: whether nuclear medicine can not only characterize the mechanisms and effects of tDCS but also contribute to optimizing its therapeutic application across neurological and psychiatric diseases (Stagg et al., 2011).

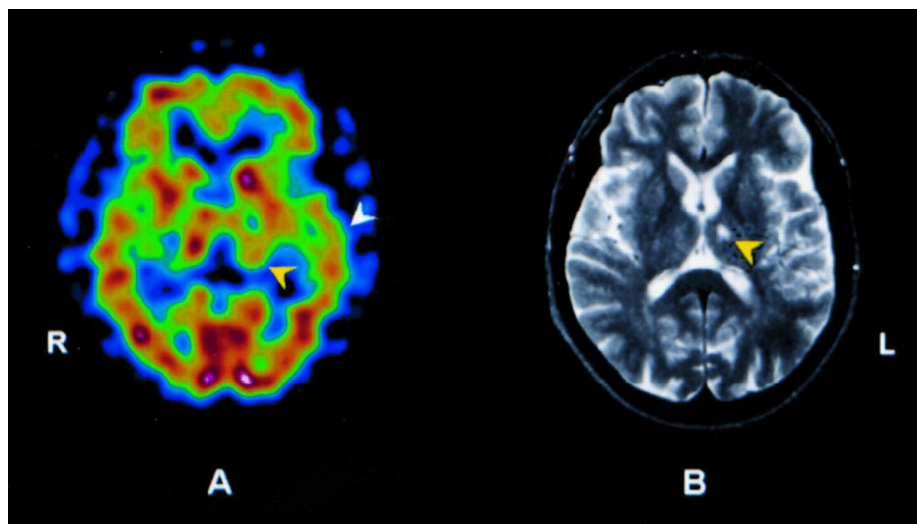
2.Methods

This manuscript adopts a narrative literature review approach focusing on mechanistic, clinical, and imaging research involving tDCS and nuclear medicine. Peer-reviewed studies were extracted from PubMed, Scopus, and Web of Science using combinations of terms including transcranial direct current stimulation, PET imaging, SPECT imaging, neuromodulation, cerebral blood flow, brain metabolism, and neurotransmitter receptors. Priority was given to studies employing PET or SPECT to investigate brain activity changes following tDCS, as well as nuclear medicine research addressing biomarkers relevant to neuromodulation and neuroplasticity. The conceptual framework guiding this review centers on three thematic domains: 1. nuclear medicine as a mechanistic tool to visualize tDCS-induced physiological and molecular changes. 2. nuclear imaging as a predictive and personalized medicine approach for tailoring tDCS interventions. 3. the hypothetical therapeutic integration of tDCS with nuclear medicine, particularly in conditions in which neuromodulation and molecular neuroimaging intersect, such as stroke, dementia, mood disorders, and movement disorders. While tDCS itself does not require imaging for administration, nuclear medicine provides a unique window into brain-wide functional modulation that may enhance the precision, dosing, and targeting of tDCS interventions. Because no standardized protocols exist for combining these modalities, this review synthesizes available evidence to outline future possibilities rather than provide statistical meta-analysis.

3.Results

Figure 1. SPECT (A) and MRI (T2-weighted) (B) slices at basal ganglia level of patient with ischemic lesion in left thalamus (yellow arrowheads). Patient developed aphasia, which could not be explained by localization of anatomic lesion only. MRI of left temporal cortex was normal, but decreased tracer uptake in region can be seen in SPECT image (white arrowhead).

This was interpreted as ipsilateral subcorticocortical deafferentation (Catafau, 2001).

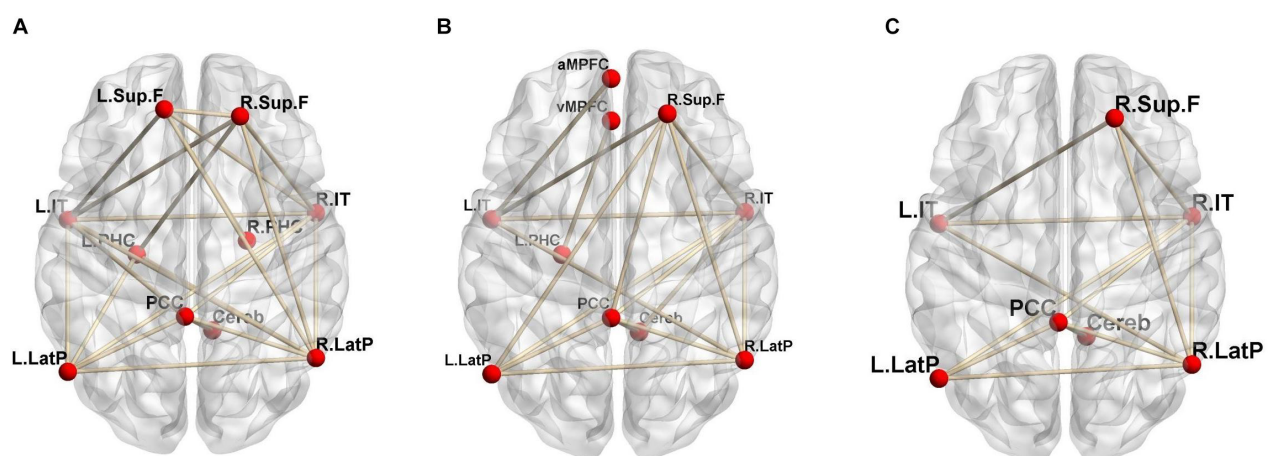


Available nuclear medicine studies demonstrate that tDCS induces measurable and regionally specific changes in brain metabolism, perfusion, and neurotransmitter systems. Early work using PET provided foundational evidence that tDCS modulates cortical glucose metabolism. Lang et al. (2005) showed that anodal stimulation over the motor cortex increases regional cerebral blood flow and enhances excitability in both stimulated and connected motor regions, suggesting network-level propagation rather than purely focal effects. Kwon et al. (2011) later reported that tDCS produced detectable changes in regional cerebral blood flow using SPECT in patients with stroke, highlighting imaging's ability to reveal interhemispheric

rebalancing important for recovery. Complementary PET research by Stagg et al. revealed that anodal tDCS reduces GABA concentration in the stimulated cortex, providing a neurochemical explanation for enhanced plasticity (Stagg et al., 2011). Further evidence comes from dopaminergic PET imaging, where studies demonstrated that prefrontal tDCS can alter striatal dopamine release—a finding relevant for depression and Parkinson's disease (Fonteneau et al., 2018). Collectively, these imaging results confirm that tDCS influences multiple physiological domains measurable through nuclear medicine, including metabolism, neurotransmission, and network function. Transcranial direct current stimulation (tDCS) operates by delivering low-intensity electrical currents to modulate cortical excitability, while nuclear medicine techniques such as PET and SPECT allow precise visualization of metabolic, perfusion-based, and molecular changes within the brain. Together, these methods provide complementary insights into how neuromodulation influences neural circuits at both functional and biochemical levels (Figure 1).

In addition to mechanistic characterization, nuclear medicine offers biomarkers that can potentially be used to personalize tDCS therapy. FDG-PET, for example, is commonly used to identify regions of hypometabolism in dementias, which may help guide stimulation targets for cognitive enhancement trials. Amyloid and tau PET imaging provide disease staging information that may determine whether neuromodulation is likely to be beneficial in early versus late Alzheimer disease. Perfusion SPECT has been explored in major depressive disorder to characterize fronto-limbic dysregulation, which aligns with common tDCS targets such as the dorsolateral prefrontal cortex (DLPFC). Studies in stroke using SPECT or perfusion PET frequently reveal areas of diaschisis—remote hypoperfusion due to focal lesions—which may guide individualized electrode montages. Nuclear medicine's ability to quantify synaptic density using tracers such as C-CUB-J similarly raises the possibility of tracking neuroplasticity induced by repeated tDCS sessions (Fonteneau et al., 2018). The clinical integration of tDCS with nuclear medicine is supported by imaging evidence demonstrating how molecular and perfusion patterns can guide stimulation strategies across neurological and psychiatric disorders. PET and SPECT biomarkers—including hypometabolism in dementia, perfusion deficits in stroke, and dopaminergic loss in movement disorders—provide objective maps that can help identify optimal stimulation targets, personalize electrode placement, and predict treatment responsiveness. These imaging-derived insights illustrate how tDCS can be aligned with molecular pathology and network dysfunction to achieve precision neuromodulation (Figure 2).

Figure 2. Significant positive functional correlations involving the DMN. (A) Correlations based on CBF; (B) CMRO₂; (C) the overlap between CBF and CMRO₂ (reprint from Aoe et al., 2018; permission obtained from the Annals of Nuclear Medicine in accordance with their open access policy) (Watabe & Hatazawa, 2019).



4. Discussion

The convergence of tDCS and nuclear medicine presents several promising but underexplored pathways for both mechanistic insight and therapeutic innovation. From a mechanistic standpoint, nuclear medicine provides objective, quantifiable measures of brain function that can validate and expand current understanding of how tDCS modulates neural circuits. PET and SPECT imaging can elucidate whether tDCS effects remain localized to the stimulation site or extend through broader networks, enabling refined selection of stimulation parameters. Moreover, neurochemical imaging offers the

potential to correlate neurotransmitter changes with clinical outcomes, contributing to the development of biomarker-driven neuromodulation strategies. Clinically, imaging biomarkers may also help identify responders to tDCS before treatment begins—a major challenge in neuromodulation research. Patients with preserved metabolic activity in targeted networks may be more likely to respond, whereas those with advanced neurodegeneration or extensive diaschisis may require modified protocols.

The therapeutic integration of nuclear medicine and tDCS remains largely conceptual but holds significant promise. For example, neuromodulation-induced increases in cerebral perfusion or receptor expression could theoretically enhance uptake of therapeutic radiopharmaceuticals in targeted brain regions. Reciprocal approaches, in which radiotracers identify optimally responsive regions or receptor populations, could further guide tDCS application. Beyond neurological disease, psychiatric conditions such as treatment-resistant depression, bipolar disorder, and addiction may benefit from combined imaging and stimulation approaches that address both functional dysregulation and molecular abnormalities. Nevertheless, major challenges remain, including the logistical and ethical considerations associated with repeated exposure to ionizing radiation, the cost of PET/SPECT imaging, and the need for standardized stimulation–imaging protocols. Despite these limitations, the growing sophistication of neuromodulation and molecular imaging technologies suggests that combined approaches may facilitate precision neurotherapy in the future.

5. Conclusion

Transcranial direct current stimulation and nuclear medicine represent complementary modalities within modern neuroscience one providing an accessible means of modulating neural activity, the other offering the most sensitive tools for visualizing and quantifying functional and molecular processes in the human brain. Evidence from PET and SPECT studies demonstrates that tDCS produces measurable changes in cerebral metabolism, cerebral blood flow, neurotransmitter systems, and network dynamics. These findings support the potential use of nuclear medicine not only to elucidate tDCS mechanisms but also to personalize treatment, monitor therapeutic response, and identify candidates most likely to benefit from stimulation. While direct therapeutic integration of tDCS and nuclear medicine remains a future possibility requiring substantial research, the conceptual framework is increasingly supported by advances in neuroimaging and neuromodulation science. The synergy between these fields may ultimately lead to more precise, biologically informed interventions for neurological and psychiatric disorders.

Funding

The authors state that they did not receive any financial support for this study.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] Lang, N., Siebner, H. R., Ward, N. S., Lee, L., Nitsche, M. A., Paulus, W., et al. (2005). How does transcranial direct current stimulation of the primary motor cortex alter regional neuronal activity in the human brain? *European Journal of Neuroscience*, 22(2), 495–504. <https://doi.org/10.1111/j.1460-9568.2005.04233.x>
- [2] Kwon, Y. H., & Jang, S. H. (2011). The effects of transcranial direct current stimulation on motor recovery in patients with stroke. *Journal of NeuroEngineering and Rehabilitation*, 8, 17. <https://doi.org/10.1186/1743-0003-8-17>
- [3] Stagg, C. J., Bestmann, S., Constantinescu, A. O., Moreno, L. M., Allman, C., Mekle, R., et al. (2011). Relationship between physiological measures of excitability and levels of GABA and glutamate in the human motor cortex. *The Journal of Physiology*, 589(Pt 23), 5845–5855. <https://doi.org/10.1113/jphysiol.2011.216978>
- [4] Fonteneau, C., Redouté, J., Haesebaert, F., Le Bars, D., Costes, N., Suaud-Chagny, M. F., et al. (2018). Frontal transcranial direct current stimulation induces dopamine release in the ventral striatum in humans. *Cerebral Cortex*, 28(7), 2636–2646. <https://doi.org/10.1093/cercor/bhx155>
- [5] Watabe, T., & Hatazawa, J. (2019). Evaluation of functional connectivity in the brain using positron emission tomography: A mini-review. *Frontiers in Neuroscience*, 13, 775. <https://doi.org/10.3389/fnins.2019.00775>
- [6] Catafau, A. M. (2001). Brain SPECT in clinical practice. Part I: Perfusion. *Journal of Nuclear Medicine*, 42(2), 259–271.

Home Accessibility Renovation for Households with Disabilities in China: International Practices and Policy Implications

Jin Chen¹, Hailang Liu², Jingru Shan¹, Zhenkun Xu^{3*}

1.School of Rehabilitation, Jiangsu Medical College, Yancheng, 224005, China

2.Yancheng Disabled Persons' Education and Rehabilitation Center, Yancheng, 224005, China

3.Centre for Rehabilitation and Special Needs Studies, Faculty of Health Sciences, Universiti Kebangsaan Malaysia, 50300 Kuala Lumpur, Malaysia

*Corresponding author: Zhenkun Xu, xzk1818@126.com

Copyright: 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY-NC 4.0), permitting distribution and reproduction in any medium, provided the original author and source are credited, and explicitly prohibiting its use for commercial purposes.

Abstract: Background: Home accessibility modifications are crucial for promoting independent living and quality of life among persons with disabilities. While developed countries have established comprehensive policy frameworks, developing nations like China face unique challenges in program design and implementation. **Objective:** This study conducts a systematic comparative analysis of home accessibility modification policies across China, Japan, Germany, and Sweden, identifying key policy dimensions and proposing evidence-based recommendations for strengthening China's policy framework. **Methods:** We employed a multi-dimensional analytical framework examining legislative foundations, eligibility criteria, funding mechanisms, and service delivery models. Data were collected from primary legislation, governmental regulations, official statistics, and peer-reviewed literature. **Results:** Significant cross-national variations exist in policy approaches. Japan and Germany utilize social insurance models with standardized assessments, Sweden adopts a universal rights-based approach, while China employs a targeted assistance model focused on economically disadvantaged households. China completed 1.28 million household renovations during its 14th Five-Year Plan, demonstrating strong implementation capacity; future policy refinement could draw on international experience to strengthen assessment standardization, broaden effective coverage, and improve the sustainability of financing. **Conclusions:** China can benefit from international experience in developing standardized assessment protocols, diversifying funding mechanisms, and establishing professional service delivery systems, while acknowledging contextual constraints unique to developing country settings.

Keywords: Home Accessibility Modification; Disability Policy; Comparative Analysis; Barrier-Free Environment

Published: Jan 16, 2026

DOI: <https://doi.org/10.62177/apjcmr.v2i1.1023>

1.Introduction

The global population of persons with disabilities is estimated at approximately 1.3 billion (about 16% of the world's population), and this proportion is expected to increase with population aging and the growing burden of chronic diseases ^[1]. As the home is the primary setting for daily living, residential accessibility is closely linked to independence, safety, and quality of life among persons with disabilities ^[2]. The International Classification of Functioning, Disability and Health (ICF)

frames disability as an outcome of interactions between health conditions and contextual factors, underscoring the critical role of modifiable environmental features—particularly within the home—in reducing activity limitations and participation restrictions^[3]. Accordingly, home accessibility modifications, including structural adaptations (e.g., ramps, widened doorways, and bathroom modifications) and the provision of assistive devices, are widely used to support aging in place and independent living. Accumulating evidence indicates that appropriately designed home modifications can reduce caregiver burden, lower fall risk, improve functional independence, and enhance overall well-being^[4, 5].

Developed countries have established a range of policy frameworks to support home accessibility modifications for persons with disabilities, reflecting different welfare traditions. Japan and Germany largely embed home modification support within social insurance–based long-term care systems with standardized eligibility assessment and defined benefit ceilings^[6, 7]. Sweden adopts a universal, rights-based model in which municipalities provide needs-based grants funded through general taxation^[8]. The United Kingdom operates a targeted scheme (e.g., the Disabled Facilities Grant) that is means-tested and delivered through local authorities^[9]. China has also made substantial strides in developing home accessibility modification policies for persons with disabilities. During the 14th Five-Year Plan period (2021–2025), China completed barrier-free renovations for 1.28 million households with severely disabled members, surpassing the original target of 1.1 million households^[10]. Despite these achievements, significant gaps persist compared to developed country models. First, China’s modification programs primarily target families in economic hardship with severely disabled members. Second, the financing mechanism relies predominantly on government fiscal allocations rather than sustainable social insurance systems. Third, standardized assessment protocols and professional service delivery systems remain underdeveloped compared to the occupational therapist-led evaluation processes prevalent in developed countries.

Comparative policy analysis offers valuable insights for improving home accessibility modification programs in developing countries. However, existing comparative studies have predominantly focused on Western developed nations, with limited attention to China’s policy approaches and the unique contextual factors shaping implementation in the world’s most populous country^[11]. Furthermore, while developed countries have accumulated decades of experience in program design, service delivery, and outcome evaluation, knowledge transfer requires careful consideration of differences in welfare traditions, housing stock characteristics, family structures, and fiscal capacities^[12]. Understanding these cross-national variations is particularly crucial as China confronts accelerating population aging—with projections indicating that individuals aged 60 and above will exceed 400 million by 2035—alongside a rapidly evolving disability support system^[13]. This study aims to conduct a systematic comparative analysis of home accessibility modification policies for families with disabilities across China, Japan, Germany, and Sweden. Based on the findings, we propose evidence-based recommendations for strengthening China’s home accessibility modification policies, with implications for other developing countries seeking to enhance support systems for persons with disabilities within resource-constrained environments.

2. Methods

2.1 Study Design

This study employs a comparative policy analysis approach, examining home accessibility modification policies across four countries: China, Japan, Germany, and Sweden. These countries were selected based on the following criteria: (1) representation of diverse welfare state models (social insurance, universal, and targeted assistance); (2) availability of comprehensive policy documentation and outcome data; (3) varying stages of population aging and disability policy development; and (4) geographic and cultural diversity to ensure broader applicability of findings. The comparative analysis follows a structured framework adapted from established health policy comparison methodologies^[14, 15].

2.2 Analytical Framework

We developed a multi-dimensional analytical framework encompassing four key policy dimensions:

Legislative and Policy Foundations: Constitutional provisions, primary legislation, and regulatory frameworks governing home accessibility modifications.

Eligibility Criteria and Assessment Systems: Target populations, assessment protocols, and certification processes for program access.

Funding Mechanisms: Financing sources (social insurance, taxation, out-of-pocket), subsidy levels, and cost-sharing arrangements.

Service Delivery Models: Professional involvement, service providers, and quality assurance mechanisms.

2.3 Data Sources

Data were collected from multiple sources, including: (1) primary legislation and governmental regulations from official legal databases of each country; (2) policy documents and implementation guidelines from relevant ministries and agencies; (3) official statistics from national statistical offices and social insurance agencies; (4) peer-reviewed academic literature identified through systematic searches of PubMed, Web of Science, and Scopus databases using keywords including “home modification,” “accessibility,” “disability policy,” “long-term care,” combined with country-specific terms; and (5) reports from international organizations, including the World Health Organization, Organisation for Economic Co-operation and Development (OECD), and European Commission. Literature searches were conducted between January and October 2024, with no language restrictions applied.

2.4 Analysis Approach

A structured comparative approach was employed, systematically analyzing each country’s policies across the four analytical dimensions. Cross-national comparisons were conducted to identify similarities, differences, and distinctive features. The analysis also considered contextual factors including welfare state traditions, demographic characteristics, housing stock features, and fiscal capacities that influence policy design and implementation. Findings were synthesized to derive policy implications and recommendations for China, with attention to transferability considerations in developing country contexts.

3.Comparative Policy Analysis

3.1 Legislative and Policy Foundations (Table 1)

3.1.1 Japan

Japan’s home accessibility modification policy is embedded within its Long-Term Care Insurance (LTCI) system, established under the Long-Term Care Insurance Act in 1997 and implemented nationwide in April 2000. Under the LTCI, all residents aged 40 and above are enrolled as insured persons, and benefits are available to those aged 65 and above, as well as to those aged 40-64 with specified age-related conditions ^[16]. Within this framework, municipalities provide an allowance for home renovation (e.g., installation of handrails and the removal of level differences) as part of in-home long-term care support, thereby institutionalizing home modification assistance within a broader long-term care arrangement. The LTCI was introduced in response to rapid population aging and the “socialization of care” principle, aiming to shift caregiving responsibility from individual families toward society while prioritizing aging in place ^[17]. Subsequent policy revisions have further strengthened preventive and community-based care orientations, while maintaining home renovation support as a component of home-based services ^[18].

3.1.2 Germany

Germany’s approach to home accessibility modification is embedded within its social insurance-based Long-Term Care Insurance system, established under the Pflegeversicherungsgesetz (Long-Term Care Insurance Act) enacted in 1994 and implemented from 1995. As a “fifth pillar” of the German social security system, long-term care insurance is mandatory for all statutory insurance members, with contributions shared between employers and employees and periodically adjusted by policy. Under the Eleventh Book of the German Social Code (SGB XI), provisions for the improvement of the home environment constitute a legally recognized benefit within the long-term care framework, enabling financial support for residential adaptations that facilitate daily functioning. The 2017 Care Strengthening Acts (Pflegestärkungsgesetze I–III) introduced a five-tier care grade classification and expanded the range of benefits, including support for individuals with cognitive impairments. Reforms in the mid-2010s also raised benefit ceilings for home environment improvement measures, thereby enhancing accessibility support under the LTCI system ^[7].

3.1.3 Sweden

Sweden’s housing adaptation policy is primarily governed by the Housing Adaptation Grant Act, first enacted in 1992 and subsequently revised. In contrast to the insurance-based models adopted in Japan and Germany, Sweden’s approach reflects

the Nordic universal welfare tradition, under which housing adaptation is framed as a needs-based statutory entitlement administered by municipalities, rather than as an insurance benefit. The Act requires municipalities to provide grants for necessary housing adaptations to persons with disabilities, based on assessed functional needs, without means testing and irrespective of housing tenure^[8]. This policy is complemented by the Planning and Building Act, which sets mandatory accessibility requirements for new construction and major renovations, as well as by Sweden's broader national disability policy framework emphasizing equality, accessibility, and full participation. Together with related disability support legislation, including the Act concerning Support and Service for Persons with Certain Functional Impairments (LSS), these measures form a comprehensive institutional context that supports independent living and social inclusion^[19].

3.1.4 China

China's legislative framework for accessibility has evolved substantially over the past two decades. The Law on the Protection of Persons with Disabilities, originally enacted in 1990 and comprehensively revised in 2008, established fundamental rights related to accessibility and barrier-free environment construction^[20]. The Regulations on the Construction of an Accessible Environment (2012) further provided China's first specialized regulatory framework in this field^[21]. Most recently, the Law of the People's Republic of China on the Construction of Accessible Environments, adopted by the National People's Congress in June 2023 and effective from September 2023, marked a major legislative advancement. This law places explicit responsibility on governments at all levels to promote accessible environment construction and includes provisions relevant to residential settings, supporting modifications that enable persons with disabilities and older adults to safely travel, enter and exit buildings, use facilities and public transportation, access information, and participate in social services^[22].

Table 1. Comparative Overview of Home Accessibility Modification Policies

Dimension	Japan	Germany	Sweden	China
Policy Model	Social Insurance (LTCI)	Social Insurance (Pflegeversicherung)	Universal Rights-based	Targeted Assistance
Year Established	2000	1995	1992	2012 (Regulation) / 2023 (Law)
Primary Legislation	Long-Term Care Insurance Act	SGB XI (Social Code Book XI)	Housing Adaptation Grant Act	Law on Barrier-Free Environments
Target Population	Age 65+ ; or 40-64 with specified conditions	Insured persons with assessed care needs (Pflegegrad)	Persons with disabilities based on assessed functional needs (no means testing)	Severely disabled persons in economic hardship
Maximum Subsidy	¥200,000 per beneficiary (home renovation allowance)	€4,000 per measure	Needs-based coverage of approved costs	Variable by region (¥2,000-8,000)
Funding Source	Insurance premiums + taxes + copayment (typically 10-30%)	Insurance premiums (employer/employee)	Municipal taxation	Government fiscal allocation
Assessment Method	Standardized eligibility assessment + care manager (care plan)	MD assessment, 5-tier Pflegegrad	OT-led needs assessment	Disability certification + means testing and local needs assessment procedures

Note: LTCI = Long-Term Care Insurance; SGB = Sozialgesetzbuch (Social Code); MD = Medizinischer Dienst; OT = Occupational Therapist

3.2 Eligibility Criteria and Assessment Systems

3.2.1 Japan

Japan employs a comprehensive, standardized assessment system as the gateway to Long-Term Care Insurance (LTCI) benefits, including home modifications. Primary insured persons (Category 1, aged 65 and above) are eligible regardless of the cause of disability, while secondary insured persons (Category 2, aged 40-64) must demonstrate care needs arising from

specified age-related conditions. The assessment process involves a 74-item standardized questionnaire covering physical function, cognitive status, and behavioral characteristics, administered by trained municipal investigators. Responses are processed through computer-based algorithms to generate a preliminary care-need classification, which is subsequently reviewed by Care Need Certification Boards composed of physicians, nurses, and other health and social care professionals. The resulting seven-level classification—Support Levels 1–2 and Care Levels 1–5—determines the scope of available benefits. For home modifications, certified care managers conduct individualized assessments to identify appropriate adaptations based on the person’s functional limitations and residential environment^[23]. This dual-layer assessment mechanism ensures system-wide standardization while allowing for individual tailoring.

3.2.2 Germany

Germany’s assessment system was substantially reformed in 2017 with the introduction of the Pflegegrad (care grade) classification. In-home assessments are conducted by the Medical Service (Medizinischer Dienst, MD) using a standardized evaluation instrument that examines six domains: mobility; cognitive and communication abilities; behavioral and psychological problems; self-care; management of disease-related requirements; and the organization of daily life and social contacts. These domains are differentially weighted, with self-care carrying the greatest weight, to produce an overall score that is mapped onto five care grades (Pflegegrad 1–5). Individuals classified as Pflegegrad 1 exhibit minor impairments and receive limited benefits, whereas Pflegegrad 5 indicates severe functional limitations requiring intensive support. Home modification subsidies are available from Pflegegrad 1 onward, subject to a uniform ceiling of €4,000 per measure. The assessment framework explicitly recognizes the role of the home environment in maintaining independence, thereby positioning environmental adaptation as an integral complement to personal care services^[24].

3.2.3 Sweden

Sweden’s housing adaptation grant system is characterized by a needs-based approach without means testing. Individuals with permanent or long-term functional impairments that limit their ability to use their home independently may apply, regardless of age, income, or housing tenure. Assessments are conducted at the municipal level and typically involve occupational therapists, who evaluate functional limitations in relation to the specific residential environment. Rather than assigning applicants to standardized care levels, each case is assessed individually based on documented needs, often supported by medical documentation describing the functional implications of the impairment. Municipal authorities then determine whether the proposed modifications are “necessary” for the applicant’s independent functioning at home—a criterion that has occasionally been subject to legal interpretation but generally allows for a broad range of adaptations^[25]. Empirically, approximately 85% of grant recipients are aged 65 years or older, reflecting the strong association between aging and functional limitation.

3.2.4 China

China’s eligibility determination for home accessibility modifications operates through a dual criterion of disability status and household economic circumstances. Applicants are required to hold a valid disability certificate issued through the national disability assessment system, which classifies disabilities into four grades (Level I being most severe and Level IV mild) across six categories: visual, hearing, speech, physical, intellectual, and psychiatric disabilities. Current programs primarily prioritize individuals with Level I or Level II disabilities. A second eligibility criterion concerns household economic status, with priority typically given to families registered as minimum livelihood guarantee, extreme poverty, or marginal low-income households. Assessments are conducted by county- or district-level Disabled Persons’ Federations in coordination with civil affairs departments.

3.3 Funding Mechanisms

The four countries exhibit markedly different approaches to financing home accessibility modifications, reflecting broader welfare state configurations and fiscal capacities (Table 2).

Japan’s LTCI system pools resources from three main sources: insurance premiums paid by insured persons, public funding from national and local governments, and user copayments, with premiums and public funding each accounting for roughly half of total expenditures and copayments representing a smaller share^[16]. Premium rates vary across municipalities and are

income-adjusted for Category 1 insured persons (aged 65+). For home modifications, beneficiaries are eligible for coverage of up to ¥200,000 per dwelling over the lifetime, subject to a copayment typically set at 10% (and higher for higher-income beneficiaries). The lifetime cap can be reset upon relocation or substantial changes in care needs, allowing the benefit to respond to evolving functional circumstances. Overall, this insurance-based mechanism offers relatively predictable financing while incorporating cost-sharing to encourage appropriate use.

Germany's Pflegeversicherung similarly relies on mandatory premium contributions shared between employers and employees, with the contribution rate periodically adjusted by policy. The system provides subsidies of up to €4,000 per approved home modification measure, generally without direct copayment for the modification itself. Importantly, the ceiling applies per "measure" rather than per individual, meaning that households with multiple eligible members may access higher total amounts when needs are distinct. Reforms in the mid-2010s increased the benefit ceiling, improving access to adaptations, although some evidence suggests that part of the increase may have been absorbed by rising contractor prices rather than fully translating into lower out-of-pocket costs for recipients ^[7]. Unlike Japan, Germany does not impose a lifetime cap on cumulative modification benefits; additional measures may be funded as needs change.

Sweden's tax-financed system represents a universal, rights-based model. Municipalities are responsible for housing adaptation grants, financed primarily through local taxation, supplemented by fiscal equalization mechanisms. Eligible applicants are not subject to means testing or copayment requirements, and municipalities generally cover the full cost of approved and necessary modifications based on assessed need. National expenditure exceeds SEK 1 billion annually, supporting a substantial volume of adaptations each year ^[8]. While this model minimizes financial barriers, it can generate fiscal pressure for municipalities with aging populations and higher levels of functional limitation.

China's financing mechanism relies primarily on multi-level government fiscal allocations. Central government earmarked transfers are channeled through the China Disabled Persons' Federation system and supplemented by provincial and local government contributions. During the 14th Five-Year Plan period (2021–2025), substantial public investment supported large-scale implementation, including the completion of barrier-free renovations for approximately 1.28 million households by mid-2025. However, per-household subsidy levels remain modest by international standards and vary across provinces, with some localities experimenting with complementary sources such as charity donations and lottery welfare funds ^[26].

Table 2. Comparison of Funding Mechanisms and Coverage Levels

Aspect	Japan	Germany	Sweden	China
Financing Type	Social insurance + public funding	Social insurance	Tax-financed (municipal)	Government fiscal appropriation
Copayment	10–20% (income-related)	None (for approved measures)	None	None for eligible households
Means Test	No (copayment varies by income)	No	No	Yes (economic hardship criteria)
Annual Beneficiaries	Large-scale national program	Nationwide insurance-based program	70,000–75,000 approved adaptations annually	1.28 million households completed during the 14th Five-Year Plan

3.4 Service Delivery Models

Service delivery systems vary substantially across the four countries, reflecting different professional traditions and institutional arrangements.

In Japan, care managers play a central coordinating role within the Long-Term Care Insurance (LTCI) system, including home modification services. These professionals—typically nurses, social workers, or other qualified practitioners who have passed national certification examinations—conduct needs assessments, develop care plans, and coordinate services across providers. For home modifications, care managers work with designated contractors who meet prefectural registration requirements. The service delivery process emphasizes pre-modification consultation and post-modification follow-up to ensure that adaptations address actual functional needs. Building contractors, rehabilitation specialists, and welfare equipment advisors

often collaborate in the modification process. In addition, Japan has developed specialized training programs for renovation coordinators or specialists with expertise in accessibility-oriented housing adaptations, supporting professionalized service delivery^[23].

Germany's service delivery model is centered on the long-term care insurance funds, which process applications, coordinate assessments, and approve home modifications. Upon receiving a request, the Pflegekasse may involve housing counseling services, which operate in most municipalities and are commonly staffed by architects, social workers, and occupational therapists. These services provide free advice on suitable modification options and assist applicants throughout the approval process. Modifications are generally implemented by private contractors selected by beneficiaries, with costs reimbursed after completion. Quality assurance is primarily embedded in the approval and reimbursement procedures rather than standardized post-modification outcome evaluations. Recent policy initiatives emphasize closer coordination between healthcare and social care systems, with potential implications for more integrated service delivery^[24].

Sweden's decentralized system assigns primary responsibility for housing adaptation services to its 290 municipalities, resulting in some local variation in implementation. Nevertheless, occupational therapists (arbetsterapeuter) consistently occupy a central professional role in needs assessment and prescription of modifications. Following an application, municipal OTs typically conduct home visits to evaluate functional limitations and environmental barriers, and then specify the required adaptations. Municipalities may implement modifications through in-house construction teams or private contractors. A distinctive feature of the Swedish model is the integration of housing adaptation with other disability supports, such as assistive technology provision and personal assistance services, enabling comprehensive responses to independent living needs. Post-modification follow-up by OTs further supports effectiveness and adjustment where necessary^[25].

China's service delivery system for home accessibility modifications is still evolving. Implementation is typically coordinated by county- and district-level branches of the China Disabled Persons' Federation (CDPF), in collaboration with civil affairs departments and community-level organizations. Assessment and modification activities may be undertaken by CDPF staff, community workers, or contracted service providers, but professional qualifications and service capacity vary considerably across regions. Although some localities have begun to involve rehabilitation professionals and social workers, a nationally standardized, occupational therapist-led functional assessment framework has not yet been fully established. Quality assurance mechanisms are also uneven, with some provinces adopting technical standards and inspection procedures while national standardization remains limited. Recent policy emphasis on "precise" assistance reflects increasing attention to individualized needs, and although implementation challenges persist, ongoing policy refinement and local experimentation indicate gradual improvements across different contexts.

4. Discussion

This comparative analysis reveals both convergent trends and persistent differences in home accessibility modification policies across the four countries. All four nations recognize home modifications as essential supports for independent living and have established legal frameworks to facilitate access. However, the policy instruments employed—social insurance, universal entitlement, or targeted assistance—reflect different welfare state traditions and fiscal contexts.

Across countries, home accessibility modification policies reflect distinct financing and assessment approaches shaped by welfare traditions and fiscal contexts. Japan and Germany rely on social insurance-based models that offer relatively sustainable and predictable funding, supported by standardized assessments and established professional roles, though at the cost of administrative complexity and incomplete population coverage. Sweden's universal, tax-financed system provides the most inclusive access based on assessed need but places substantial fiscal responsibility on municipalities. China's targeted assistance approach has enabled rapid scale-up and effective concentration of limited resources on households with the greatest combined disability and economic need, while necessarily prioritizing coverage within existing fiscal constraints. Correspondingly, assessment systems vary: professionally administered and standardized mechanisms in Japan, Germany, and Sweden help align modifications with functional needs, whereas China's reliance on disability certification and economic eligibility, while efficient, offers a more limited basis for individualized functional assessment.

Drawing on the above comparative findings, several policy implications emerge for the continued strengthening of China's

home accessibility modification programs. While the current focus on households with severe disabilities and economic hardship has been effective in directing limited resources to those most in need—particularly during the rapid expansion phase of the 14th Five-Year Plan—a gradual expansion of eligibility to include individuals with moderate disabilities or households slightly above poverty thresholds could further enhance equity and program reach. Income-adjusted cost-sharing mechanisms, similar to those used in Japan, may help balance expanded access with fiscal sustainability, a direction supported by the legal foundation established under the 2023 Law on the Construction of Accessible Environments. At the same time, international experience underscores the importance of standardized, professionally administered functional assessments in improving the appropriateness and effectiveness of home modifications. China could develop assessment tools tailored to domestic conditions, drawing on the ICF framework and adapting elements from Japan and Germany, while strengthening training for rehabilitation professionals, social workers, and community health workers to build long-term professional capacity. In terms of financing, although reliance on fiscal appropriations has enabled rapid implementation, exploring hybrid funding models—such as greater integration with long-term care insurance pilots, alongside government subsidies, charitable contributions, and carefully designed user copayments—could enhance financial resilience and program continuity. Finally, strengthening service delivery infrastructure through workforce development, technical standards, and quality assurance mechanisms, together with differentiated strategies to address urban–rural disparities in housing conditions and service availability, would support more consistent and effective implementation across diverse local contexts.

At the same time, policy learning from developed countries must be carefully contextualized. China’s housing stock differs markedly from that of Japan, Germany, and Sweden, characterized by high rates of multi-generational living, diverse construction forms ranging from traditional courtyard dwellings to high-rise apartments, and complex property rights arrangements. Family structures and caregiving norms also differ, with family-based care remaining more prominent in China, which may moderate demand for formal modification services while increasing the importance of adaptations that support family caregivers. Fiscal capacity represents an additional constraint: although China’s overall economic scale has expanded substantially, per capita GDP and government revenue remain below those of most developed countries, making the generous subsidy levels and universal coverage observed in countries such as Sweden difficult to replicate in the short term. Nevertheless, China’s strong administrative capacity and demonstrated ability to implement large-scale programs—evidenced by the successful completion of approximately 1.28 million household accessibility modifications during the 14th Five-Year Plan—provide a solid foundation for continued policy refinement and gradual expansion.

This study has several limitations. First, data availability and quality vary across countries, limiting comparability of some metrics. Second, policy documents may not fully capture implementation realities, and grassroots-level challenges may be underrepresented. Third, the analysis focuses on policy frameworks rather than outcome evaluations, which remain limited, particularly for China’s programs. Future research should examine program effectiveness and beneficiary outcomes across different policy models.

5. Conclusion

Drawing on international experience, China can further strengthen home accessibility modification policies through gradual expansion of eligibility, the development of standardized and professionally administered functional assessments, diversified financing—including closer integration with emerging long-term care insurance—enhanced workforce training and service delivery capacity, and context-sensitive strategies to address urban–rural differences. As China responds to rapid population aging and advances disability rights and barrier-free environment construction, these reforms offer a practical pathway to improving quality of life for millions of persons with disabilities and older adults, while China’s experience in scaling up large-scale programs may also provide useful lessons for other countries pursuing inclusive development.

Funding

This research was funded by the China Disabled Persons’ Federation under its 2024 research project (Grant No. 2024CDPFAT-47) and the Yancheng Social Science Foundation (Grant No. 25skB252). The funding agencies did not contribute to the experimental design or conclusions.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] World Health Organization. (2023). Disability. Retrieved from <https://www.who.int/news-room/fact-sheets/detail/disability-and-health>
- [2] Iwarsson S, Ståhl A. (2003). Accessibility, usability and universal design--positioning and definition of concepts describing person-environment relationships. *Disabil Rehabil*, 25(2), 57–66.
- [3] World Health Organization. (2001). International Classification of Functioning, Disability and Health (ICF). Retrieved from <https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health>
- [4] Carnemolla P, Bridge C. (2019). Housing Design and Community Care: How Home Modifications Reduce Care Needs of Older People and People with Disability. *International Journal of Environmental Research and Public Health*, 16(11), 1951.
- [5] Keall M D, Piers N, Howden-Chapman P, et al. (2015). Home modifications to reduce injuries from falls in the home injury prevention intervention (HIPI) study: a cluster-randomised controlled trial. *Lancet*, 385(9964), 231–8.
- [6] Suyama N, Inoue K, Kuniya S, et al. (2024). History of assistive devices and home modification services under long-term care insurance system in Japan across 20 years: A narrative review. *Assist Technol*, 36(6), 412–21.
- [7] Joo B. (2017). The Effect of Increases in German Long-Term Care Insurance Subsidies for Senior-Friendly Housing. *Innovation in Aging*, 1(suppl_1), 457–8.
- [8] Slaug B, Chiatti C, Oswald F, et al. (2017). Improved Housing Accessibility for Older People in Sweden and Germany: Short Term Costs and Long-Term Gains. *Int J Environ Res Public Health*, 14(9),
- [9] Gov.Uk. (2022). Disabled Facilities Grant (DFG) delivery: guidance for local authorities in England. Retrieved from <https://www.gov.uk/government/publications/disabled-facilities-grant-dfg-delivery-guidance-for-local-authorities-in-england>
- [10] The State Council Information Office of the People's Republic of China. (2025). High-Quality Completion of the Thematic Press Conference Series on the 14th Five-Year Plan. Retrieved from <http://www.scio.gov.cn/live/2025/36823/qwxz/202507/P020250723376810107031.pdf>
- [11] Wu Y, Zhang L, Fang X. (2022). Evidence review of home adaptations in the UK and selected OECD countries. Retrieved from
- [12] Tervonen-Gonçalves L, Lehto J. (2004). Transfer of Health for All policy - What, how and in which direction? A two-case study. *Health Res Policy Syst*, 2(1), 8.
- [13] National Health Commission of China. (2024). Report on the Development of Health Undertakings for the Aged in China. Retrieved from
- [14] Marmor T, Freeman R, Okma K. (2005). Comparative Perspectives and Policy Learning in the World of Health Care. *Journal of Comparative Policy Analysis: Research and Practice*, 7(4), 331–48.
- [15] Blank R H, Burau V. (2014). Comparative health policy. In *Book Comparative health policy* (pp. Palgrave Macmillan.
- [16] Tamiya N, Noguchi H, Nishi A, et al. (2011). Population ageing and wellbeing: lessons from Japan's long-term care insurance policy. *Lancet*, 378(9797), 1183–92.
- [17] Campbell J C, Ikegami N. (2000). Long-term care insurance comes to Japan. *Health Aff (Millwood)*, 19(3), 26–39.
- [18] Ministry of Health L a W. (2024). Long-Term Care Insurance System of Japan. Retrieved from <https://www.mhlw.go.jp/english/policy/care-welfare/care-welfare-elderly/>
- [19] Swedish Institute. (2024). Disability policy in Sweden. Retrieved from <https://sweden.se/life/equality/disability-policy>
- [20] (2008). Law of the People's Republic of China on the Protection of Persons with Disabilities. Retrieved from https://www.gov.cn/guoqing/2021-10/29/content_5647618.htm
- [21] State Council of the People's Republic of China. (2012). Regulations on the construction of barrier-free environments.

Retrieved from https://www.gov.cn/zwgk/2012-07/10/content_2179864.htm

- [22] Standing Committee of the National People's Congress.(2023). Law of the People's Republic of China on the Construction of Accessible Environments. Retrieved from https://www.gov.cn/yaowen/liebiao/202306/content_6888910.htm
- [23] Makigami K, Pynoos J. (2002). The evolution of home modification programs in Japan. *Ageing International*, 27(3), 95–112.
- [24] Bundesgesundheitsministerium. (2024). Long-term care insurance. Retrieved from <https://www.bundesgesundheitsministerium.de/en>
- [25] Iwarsson S, Slaug B. (2010). Housing Enabler: A method for rating/screening and analysing accessibility problems in housing. In Book *Housing Enabler: A method for rating/screening and analysing accessibility problems in housing* (pp. Vetén & Skansen.
- [26] Wu Y, Zhang L, Fang X. (2022). Evidence review of home adaptations in the UK and selected OECD countries. *International Journal of Environmental Research and Public Health*, 19(3),

The Role and Mechanism of Acupuncture Analgesia in the US Opioid Crisis Research

Tingting Zhu*, Chengbo Zhen

Summer Acupuncture, San Jose, CA, 95117, USA

*Corresponding author: *Tingting Zhu, summeracu01@gmail.com*

Copyright: 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY-NC 4.0), permitting distribution and reproduction in any medium, provided the original author and source are credited, and explicitly prohibiting its use for commercial purposes.

Abstract: The US opioid crisis has become a serious public health issue, causing tens of thousands of deaths and tremendous economic loss annually. Acupuncture, as a traditional non-pharmacological method of analgesia, has demonstrated extraordinary value in addressing this crisis. This paper systematically elucidates the causes and impacts of the US opioid crisis and deeply explores the neurobiological mechanisms of acupuncture analgesia, including the activation of the endogenous opioid system, neurotransmitter regulation, and anti-inflammatory and immune modulation via multiple pathways. By analyzing the clinical evidence for acupuncture in the management of acute and chronic pain, opioid dosage reduction, and addiction treatment, we demonstrate the feasibility and efficacy of acupuncture as an alternative to opioid therapy. Research shows that acupuncture can not only effectively relieve various types of pain but also reduce opioid consumption and treat opioid dependence and addiction. However, the promotion of acupuncture in the US still faces multi-faceted challenges, including issues of standardization, limited insurance coverage, and insufficient high-quality evidence. Future efforts should focus on strengthening multidisciplinary research collaboration, improving standardized treatment protocols, and integrating acupuncture into comprehensive pain management systems to provide a safer, more cost-effective, non-pharmacological alternative for resolving the opioid crisis.

Keywords: Acupuncture; Analgesic Mechanism; Opioid Crisis; Pain Management; Non-pharmacological Therapy

Published: Jan 16, 2026

DOI: <https://doi.org/10.62177/apjcmr.v2i1.917>

1.Introduction

The US opioid crisis is one of the most severe public health disasters of the 21st century. Since the late 1990s, the over-prescription and misuse of opioid medications have led to a sharp rise in addiction and death rates. According to data from the US Centers for Disease Control and Prevention (CDC), approximately 860,000 Americans died from an opioid overdose between 1999 and 2023 ^[1]. Approximately 105,000 people died from drug overdose in 2023, nearly 80,000 of which involved opioids (approximately 76%). The number of people who died from an opioid overdose in 2023 was nearly 10 times the number in 1999 ^[2]. This crisis has not only caused massive human casualties but has also imposed a heavy burden on the socioeconomic structure, with estimated annual losses exceeding trillions of dollars. On August 10, 2017, President Trump declared the opioid crisis a national public health emergency. It was estimated that the economic cost of the US opioid crisis in 2017 was \$1.021 trillion, including an estimated \$471 billion for the cost of opioid use disorder and an estimated \$550 billion for the cost of fatal opioid overdose ^[3].

The root of the opioid crisis lies in the imbalance of pain management strategies. For a long time, opioids were considered the primary treatment for chronic pain, but their high addictiveness and serious side effects have become increasingly apparent. Finding safe and effective non-pharmacological methods for analgesia has become an urgent priority. Against this backdrop, on July 13, 2017, the US National Academies of Sciences (NAS), Engineering (NAE), and Medicine (NAM) jointly released a report, “Pain Management and the Opioid Epidemic: Balancing Societal and Individual Benefits and Risks of Prescription Opioid Use,” which dedicated a chapter to the clinical study of acupuncture for various types of pain, recognizing it as a potentially effective non-pharmacological therapy for pain ^[4]. Subsequently, the American Society of Acupuncturists (ASA) and six collaborating organizations jointly published a white paper titled “The Role of Acupuncture in Addressing the Opioid Crisis: Evidence, Cost and Health Services Feasibility of Acupuncture as a First-Line Non-Pharmacological Therapy for Treatment and Control of Pain” ^[5, 6].

In response to the risks of pharmacological treatments for acute and chronic pain and the ongoing opioid crisis, the US CDC and the Food and Drug Administration (FDA) recommend non-pharmacological pain management methods as first-line care. Acupuncture has been listed as a preferred first-line option by the Army Surgeon General’s Pain Management Task Force and the American College of Physicians (ACP). The Agency for Healthcare Research and Quality (AHRQ), the National Institutes of Health (NIH), and the National Academy of Medicine have all included acupuncture as part of comprehensive pain care ^[7]. Acupuncture, a traditional Chinese medical therapy with thousands of years of history, has received increasing attention due to its significant analgesic effects, minor side effects, non-addictive nature, and low cost.

This paper aims to comprehensively analyze the role and mechanisms of acupuncture analgesia in addressing the US opioid crisis. It demonstrates that integrating acupuncture into the pain management system can not only alleviate the American healthcare burden but also offer patients more treatment options, reduce opioid dependence, and thereby lower the risk of addiction and mortality.

2. Overview of the US Opioid Crisis

2.1 Analysis of the Crisis’s Causes

The etiology of the opioid crisis is complex and multi-factorial. The initial catalyst was the healthcare system’s reliance on pharmacological solutions, compounded by the intense pressure on clinicians to alleviate pain—a measure categorized by the World Health Organization (WHO) as the “fifth vital sign,” alongside standard metrics like blood pressure and temperature. Pharmaceutical corporations aggressively promoted their products, using deceptive marketing to assure the medical community that opioids were safe for the extended management of chronic non-cancer pain, minimizing concerns about dependency. This challenge was subsequently magnified by inadequate regulatory oversight. Early, lax standards for opioid prescriptions permitted physicians to readily dispense substantial drug quantities, while the absence of effective patient education and robust risk assessment mechanisms meant many individuals initiated use without recognizing the significant addiction risks. Furthermore, the problem was intensified by a dearth of accessible alternative treatments; safer options, such as physical therapy and acupuncture, were frequently underutilized due to insufficient insurance coverage and limited availability. Finally, socioeconomic factors provide an underlying context, as economic hardship, unemployment, and social isolation are strongly correlated with heightened drug abuse risk, leading to opioid addiction rates significantly exceeding the national average in regions experiencing economic downturn.

2.2 Scale and Impact of the Crisis

The magnitude of the opioid crisis is staggering, representing a pervasive societal issue that transcends specific demographics, affecting individuals across all ages, racial groups, and socioeconomic strata. While its reach is broad, certain populations have been disproportionately impacted, notably middle-aged white males, residents of rural areas, and low-income communities.

The resultant economic toll is immense, extending far beyond direct healthcare expenditures. The overall financial burden encompasses substantial costs related to diminished labor force productivity, expenses within the criminal justice system, and greatly increased child welfare expenditures. The widespread prevalence of opioid addiction has driven a dramatic surge in social crises, including increased family dissolution, child neglect, and abuse. Furthermore, the crisis has led to a noticeable

decline in labor force participation across numerous communities, directly undercutting regional economic vitality and growth.

3. Neurobiological Mechanisms of Acupuncture Analgesia

3.1 Activation of the Endogenous Opioid System

One of the core mechanisms of acupuncture analgesia is the activation of the body's endogenous opioid peptide system. Research indicates that needling stimulation promotes the release of endogenous opioid peptides such as β -endorphin, enkephalin, and dynorphin from the central nervous system. These substances bind to opioid receptors (μ , δ , κ type) to produce analgesic effects, raising the pain threshold and decreasing pain sensitivity. Animal experiments confirm that the use of the opioid receptor antagonist naloxone can partially block the analgesic effect of acupuncture. Other studies have shown that intracerebroventricular or intrathecal injection of cholecystokinin octapeptide (CCK-8), an endogenous opioid antagonist, can block the analgesia induced by morphine or electroacupuncture (EA) in rats^[8]. This suggests that an opioid mechanism is involved in mediating acupuncture analgesia. Different frequencies of electroacupuncture stimulation can selectively release different endogenous opioid peptides. Low-frequency EA (2 Hz) is mediated by μ and δ opioid receptors, stimulating the CNS network to release β -endorphin, enkephalin, and endorphin, while high-frequency EA (100 Hz) is mediated by κ opioid receptors, releasing dynorphin^[9]. The alternating use of high and low-frequency EA stimulation may offer additional analgesic benefits by activating both systems simultaneously^[10]. This frequency-dependence provides a theoretical basis for the individualization and precision of acupuncture treatment.

3.2 Regulation of Neurotransmitters

In addition to the opioid peptide system, acupuncture also produces analgesic effects by regulating multiple neurotransmitters. The 5-hydroxytryptamine (5-HT) system is an important descending inhibitory pathway, and serotonin (5-HT) was hypothesized as an analgesic neurotransmitter in early studies^[11]. Research shows that acupuncture can increase the pain threshold, and this analgesic effect is attenuated after injection of p-chlorophenylalanine (a serotonin synthesis inhibitor)^[12]. Therefore, serotonin is considered to play a major role in acupuncture analgesia.

The norepinephrine (NE) system is also involved in acupuncture analgesia. Norepinephrine-containing neurons originate from various brain regions, including the raphe nuclei, locus coeruleus, periaqueductal gray, and the A1, A2, and A4-A7 nuclei of the brainstem. These neurons project to the forebrain and descend along the dorsolateral funiculus of the spinal cord, playing a role in pain modulation. Acupuncture can activate the locus coeruleus in the brainstem, increasing NE release, and inhibiting nociceptive transmission in the spinal dorsal horn via α 2-adrenergic receptors^[13]. Recent research has also found that acupuncture can regulate the adenosine system. Adenosine concentration is significantly elevated in local tissues after needling, producing a local analgesic effect by activating the A1 receptor. This finding reveals the peripheral mechanism of acupuncture's action, providing a new perspective for understanding the immediate analgesic effect of needling^[14].

3.3 Neuroinflammation and Immune Regulation

Chronic pain is often accompanied by neuroinflammatory responses. Acupuncture has anti-inflammatory effects. Studies indicate that chronic electroacupuncture (EA) can decrease the activity of T and B lymphocytes in the lymph nodes of mice with collagen-induced arthritis^[15]. In another study, the activity of splenic Natural Killer (NK) cells was enhanced in mice after chronic EA, an effect that could be eliminated by injecting the endorphin antagonist naloxone^[16]. Furthermore, studies have found that acupuncture can reduce the release of pro-inflammatory factors and increase the production of anti-inflammatory factors. In addition, acupuncture can regulate the vagus nerve-cholinergic anti-inflammatory pathway. This is a crucial neuro-immune regulatory pathway that suppresses peripheral inflammatory responses by releasing acetylcholine. Needling specific acupoints can activate this pathway, producing a systemic anti-inflammatory effect^[17]. These immune regulatory effects help to alleviate inflammatory pain.

3.4 Inhibition of Central Sensitization

A key pathological mechanism of chronic pain is central sensitization, which is the enhanced responsiveness and lowered threshold of the central nervous system to painful stimuli. Numerous documented studies indicate that the signaling system of glutamate and its receptors is crucial in the processing of spinal nociception and central sensitization^[18]. Acupuncture can

suppress central sensitization through multiple pathways. Firstly, needling can reduce the release of excitatory amino acids (such as glutamate), decreasing the excitability of spinal dorsal horn neurons. Secondly, immunochemical studies revealed that 2 Hz electroacupuncture (EA) administered to rats with neuropathic pain not only alleviated the pain but also reduced the expression of the NMDA receptor subunit NR1 in the spinal dorsal horn^[19]. Choi et al. used a similar method but studied CFA-induced inflammatory pain rats and found that the expression of both NR1 and NR2A NMDA receptor subunits was reduced in the spinal dorsal horn^[20]. This suggests that acupuncture can regulate the expression and function of NMDA receptors, which are key molecular mechanisms in the formation of central sensitization.

Long-term repeated acupuncture treatment can reverse neuroplastic changes caused by chronic pain. After nerve injury, hyperexcitability similar to long-term potentiation (LTP) may occur in spinal nociceptive synaptic transmission, which may be the basis for neuropathic pain. Animal studies show that long-term depression (LTD) of synaptic strength in the spinal dorsal horn may be the underlying mechanism for the differential analgesic effects of low- and high-frequency EA in neuropathic pain. Therefore, the direction of long-term synaptic plasticity, similar to LTP or LTD, in the spinal dorsal horn may determine the onset or inhibition of neuropathic pain^[21]. Acupuncture can restore the function of inhibitory neurons in the spinal cord and brain, re-establishing the excitation-inhibition balance, thereby alleviating chronic pain states. This action may explain the long-term efficacy of acupuncture in chronic pain.

In summary, the neurobiological mechanisms of acupuncture analgesia are multi-target and multi-level, involving multiple systems from the periphery to the central nervous system. By mechanically stimulating acupoints, afferent nerve signals are activated, leading to the release of analgesic substances from the central nervous system (especially the endogenous opioid system) and modulating brain regions related to pain perception, emotion, and cognition, thus achieving a multi-level, holistic analgesic effect.

4. Clinical Application of Acupuncture in Pain Management

4.1 Evidence for Acupuncture Treatment of Acute Pain

Research indicates that acupuncture not only has significant therapeutic effects on various chronic pains, but its role in acute pain is even more striking. It is reported that over 50% of chronic opioid use begins in an acute pain care setting, and acupuncture may be able to reduce this risk. Arya Nielsen et al. conducted a study on acupuncture therapy as an evidence-based, non-pharmacological strategy for integrated acute pain care, updating the evidence base for acupuncture in acute pain by reviewing 22 systematic reviews and meta-analyses on post-operative and peri-operative pain (including opioid-sparing effects) and acute non-surgical and traumatic pain (including acute pain in the Emergency Department). The study found that acupuncture therapy is an effective strategy for treating acute pain, with the potential to avoid or reduce reliance on opioids. Acupuncture treatment for acute pain has a very low risk and is an important strategy in comprehensive acute pain care^[22].

4.2 Evidence for Acupuncture Treatment of Chronic Pain

Chronic pain is the main indication for opioid prescriptions and the most widespread area of acupuncture application. Extensive clinical studies and systematic reviews confirm the effectiveness of acupuncture in treating various types of chronic pain.

4.2.1 Chronic Low Back Pain:

This is one of the most common types of chronic pain and a major reason for opioid prescriptions. Cochrane reviews and other systematic reviews consistently show that acupuncture is more effective in reducing pain intensity and mildly improving function in patients with chronic low back pain compared to no treatment or usual care (such as medication, rest advice). Multiple high-quality Randomized Controlled Trials (RCTs) show that acupuncture treatment for chronic low back pain is superior to conventional treatment or sham acupuncture^[23]. A prominent large-scale study involving 1,162 patients found that those receiving acupuncture had significantly better pain relief and functional improvement than the control group, with effects lasting at least 6 months^[24].

4.2.2 Osteoarthritis Pain:

Knee and hip osteoarthritis are major sources of chronic pain in the elderly. Acupuncture shows good results in the management of osteoarthritis pain. A meta-analysis of 16 RCTs involving 3,498 patients with knee and hip osteoarthritis showed that

acupuncture significantly reduced pain and improved joint function compared to sham acupuncture^[25]. Clinical guidelines from the American College of Rheumatology list acupuncture as a conditional recommendation for knee osteoarthritis treatment.

4.2.3 Chronic Neck Pain:

Acupuncture also has a definite effect on chronic neck pain. A systematic review of 18 RCTs explicitly noted that acupuncture, as an adjunctive therapy, provides sustained pain relief for at least 3 months and shows efficacy in improving functional disability that lasts beyond 3 months. This is a distinct advantage of acupuncture's efficacy, indicating that it positively impacts the improvement of patients' daily activities and functional limitations^[26].

4.2.4 Migraine and Tension-Type Headaches:

Acupuncture has a long history in the prevention and treatment of headaches. A Cochrane systematic review including 22 RCTs with 4,985 migraine patients found that acupuncture can reduce the frequency of migraine attacks, with effects comparable to prophylactic medication but with fewer side effects^[27]. For tension-type headache, acupuncture also shows good results, superior to usual care and sham acupuncture^[28].

4.3 Evidence of Acupuncture Reducing Opioid Use

A growing number of studies are focusing on the role of acupuncture in reducing opioid use. This has direct implications for addressing the opioid crisis. A study evaluated 172 adult patients who received acupuncture treatment at a US Air Force Medical Center for at least 4 times over a year. The assessment measured changes in the volume of prescriptions for opioids, muscle relaxants, benzodiazepines, and non-steroidal anti-inflammatory drugs (NSAIDs) in the 60 days before the first acupuncture treatment and the corresponding 60 days one year later, as well as changes in "Measure Yourself Medical Outcome Profile" scores for symptoms, activity, and quality of life. The results found that patients' opioid prescriptions decreased by 45%, muscle relaxants by 34%, NSAIDs by 42%, and benzodiazepines by 14%. Additionally, patients showed improvement in symptom control, functional capacity, and well-being. This study demonstrates the feasibility of acupuncture as an opioid-sparing strategy^[29].

In post-operative pain management, acupuncture has also shown an effect in reducing opioid use. Reports suggest that acupuncture can reduce post-operative opioid requirements by over 60%^[5]. Acupuncture can also reduce common side effects like nausea and vomiting. This has been verified in various types of surgeries, including neurosurgery, gynecological surgery, and abdominal surgery^[30].

A preliminary randomized controlled trial also showed that in patients with non-malignant chronic pain, electroacupuncture reduced opioid use by 39%, an effect that persisted for 8 weeks after the EA treatment stopped^[31]. Another study targeting cancer pain patients found that acupuncture and/or acupressure in six randomized controlled trials was significantly associated with reduced cancer pain and decreased use of morphine analgesics^[32]. These studies demonstrate that acupuncture can effectively reduce patient pain and opioid consumption in both non-malignant and cancer pain, improving patients' quality of life, further proving that acupuncture can serve as an effective complementary or alternative therapy to opioids.

4.4 Application of Acupuncture in Opioid Addiction Treatment

Acupuncture can not only reduce opioid use but also be used to treat opioid addiction. Auricular acupuncture is the most commonly used method, especially the NADA (National Acupuncture Detoxification Association) protocol, which involves needling five points on the ear: Shenmen, Sympathetic, Kidney, Liver, and Lung.

Clinical studies show that acupuncture can alleviate opioid withdrawal symptoms, including anxiety, insomnia, muscle pain, and irritability. A study by Guangzhou University of Chinese Medicine indicated that acupuncture treatment could significantly reduce methadone maintenance dosage and opioid craving, and improve sleep quality to a certain extent. This research provides reliable clinical evidence for acupuncture intervention in methadone dose reduction^[33]. This demonstrates that acupuncture can increase the success rate of withdrawal and reduce relapse rates in patients with opioid addiction.

The mechanism of acupuncture in opioid addiction treatment may include: regulating the dopamine system, reducing drug craving; activating the endogenous opioid peptide system, alleviating withdrawal symptoms; regulating stress response, improving emotional state; and improving sleep quality, promoting recovery. Many detoxification centers have integrated

acupuncture into their comprehensive treatment programs as a complement to medication-assisted treatment.

4.5 Safety of Acupuncture Treatment

A major advantage of acupuncture is its high safety profile. Large-scale studies show that the incidence of serious adverse events from acupuncture is extremely low, at approximately 7.98 per 1 million treatments. Minor adverse events occur 9.4 times per 100 treatments. Half of these adverse events are localized bleeding, pain, or redness at the needling site, which are often considered expected treatment responses and are usually self-limiting, requiring no special handling^[34]. Compared to opioids, acupuncture has no risk of addiction, respiratory depression, constipation, or other severe side effects. This makes acupuncture particularly suitable for patients requiring long-term pain management, as well as those sensitive to drug side effects or with a history of substance abuse.

5. Current Status and Challenges of Acupuncture Application in the US

Acupuncture's integration into the United States healthcare system began in the 1970s and is now a well-established practice, with all fifty states regulating and licensing an estimated 50,000 practitioners who provide millions of treatments annually. Its acceptance is expanding significantly, with prestigious institutions like the Mayo Clinic and Cleveland Clinic offering these services, and the Centers for Disease Control and Prevention (CDC) recommending it as a non-pharmacological option to address the opioid crisis. A major step toward broader access was the 2020 decision by Medicare to cover acupuncture for chronic lower back pain. However, widespread utilization faces several persistent barriers: the inconsistent insurance coverage often results in high out-of-pocket costs that undermine the sustainability of long-term treatment. On the patient side, the fear of needles remains an obstacle for many potential users. Finally, a significant lack of public awareness means many beneficiaries are unaware of the conditions acupuncture can treat or how to find a qualified provider.

6. Integration of Acupuncture with Comprehensive Pain Management

Modern pain medicine increasingly champions a multimodal or comprehensive approach to managing pain, acknowledging its multifaceted nature which encompasses physiological, psychological, and social dimensions. This strategy mandates the synergistic use of diverse treatment modalities to enhance efficacy. Typically, comprehensive pain management incorporates a range of therapies, including prescribed medication, physical rehabilitation, exercise regimens, psychological counseling, massage, and acupuncture. This multi-pronged technique allows clinicians to target various pain aspects simultaneously, thereby augmenting overall treatment effectiveness and mitigating the limitations and adverse effects associated with reliance on a single intervention.

Acupuncture serves as a particularly effective non-pharmacological treatment, lending itself well to integration with other therapies for more holistic pain relief. It functions as a valuable alternative or complement to opioid medications, aiding in the reduction of drug dependency while simultaneously improving both emotional distress and physical discomfort. Notably, the military and Veterans Health Administration (VA) systems have been pioneers in integrating this approach. Numerous VA medical centers and military installations have successfully implemented programs, such as "Battlefield Acupuncture," to offer rapid pain relief to veterans and injured service members. The successful deployment and experience garnered from these initiatives provide a practical model for adoption within the civilian healthcare sector.

7. Future Research Directions and Policy Recommendations

Despite the substantial advancements achieved in research concerning acupuncture analgesia, several critical questions remain unanswered, necessitating further investigation and systemic change.

Primarily, there is an urgent need for more high-quality, large-sample randomized controlled trials (RCTs) to precisely evaluate acupuncture's efficacy across various pain conditions. These studies must move beyond assessing immediate pain reduction to focus on long-term effectiveness and robust cost-effectiveness analyses, particularly through direct comparative studies against current standard pharmacological treatments.

Secondly, realizing the full potential of acupuncture as a key strategy to mitigate the opioid crisis requires stronger policy support. Crucial governmental actions include expanding insurance coverage for acupuncture services, increasing dedicated funding for research into its mechanisms and applications, and strengthening the professional standards for acupuncturist

training and certification. Concurrently, enhancing public awareness through comprehensive public education initiatives is vital to foster broader acceptance and greater utilization of this valuable non-pharmacological treatment option.

8. Conclusion and Outlook

The ongoing US opioid crisis remains a formidable public health issue demanding an urgent, comprehensive, and multi-faceted strategic response. Within this framework, acupuncture, recognized as a safe and effective non-pharmacological analgesic, demonstrates unique value and immense potential.

Future direction lies in the integration of acupuncture into comprehensive pain management protocols. By incorporating it into a multi-modal system—synergizing with medication, physical therapy, and psychological intervention—clinicians can offer patients more personalized and thorough treatment choices. The establishment of dedicated integrated pain centers and integrative medicine facilities provides the necessary infrastructure for this integration.

The role of acupuncture in tackling the opioid epidemic is expected to significantly expand as research deepens, evidence accumulates, and policy support grows. It is poised to become one of the mainstream options for managing chronic pain, helping numerous individuals avoid or overcome opioid dependence and achieve safer, more effective analgesia.

Crucially, acupuncture is not a standalone remedy; it must function as a component of a comprehensive treatment strategy. In some cases, opioids remain necessary and appropriate treatment choices, with the key being rational use and avoiding misuse. Ultimately, resolving the opioid crisis requires a unified effort across the entire healthcare system and society, involving the reform of pain management practices, stricter prescription regulation, the expansion of alternative treatment options, the provision of robust addiction services, and the resolution of underlying socioeconomic disparities.

As a vital and increasingly integrated component of this expansive strategy, acupuncture can make a unique contribution. Through continued scientific investigation, supportive policy, collaborative professional efforts, and public awareness campaigns, we are confident that acupuncture will play a progressively significant role in improving patient health outcomes, reducing opioid-related harm, lessening the burden on the US healthcare system, and enhancing overall public well-being.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] Wide-ranging online data for epidemiologic research (WONDER). (2023). Atlanta, GA: CDC, National Center for Health Statistics. Available at <http://wonder.cdc.gov>.
- [2] Garnett, MF., & Miniño, AM. (2024). Drug overdose deaths in the United States, 2003–2023. NCHS Data Brief, (522). Hyattsville, MD: National Center for Health Statistics. doi:10.15620/cdc/170565.
- [3] Florence, C., Luo, F., & Rice, K. (2021). The economic burden of opioid use disorder and fatal opioid overdose in the United States, 2017. *Drug and Alcohol Dependence*, 218, 108350. doi.org/10.1016/j.drugalcdep.2020.108350.
- [4] The National Academies of Sciences, Engineering and Medicine. (2017). National strategy to reduce the opioid epidemic, an urgent public health priority, presented in new report [EB/OL]. <https://www.nationalacademies.org/news/new-report-presents-national-strategy-to-reduce-opioid-epidemic>.
- [5] Fan, AY., Miller, DW., Bolash, B., et al. (2017). Acupuncture's Role in Solving the Opioid Epidemic: Evidence, Cost Effectiveness, and Care Availability for Acupuncture as a Primary, Non-Pharmacologic Method for Pain Relief and Management, White Paper 2017. *Journal of Integrative Medicine*, 15(6), 411–425. doi.org/10.1016/S2095-4964(17)60378-9.
- [6] Ouyang, H., Fan, Y., Gong, C., et al. (2018). The Opioid Crisis in the United States and the Opportunities for Acupuncture Development. *Guiding Journal of Traditional Chinese Medicine and Pharmacology*, 24(5), 1–9.
- [7] Nielsen, A., & Wieland, L. S. (2019). Cochrane reviews on acupuncture therapy for pain: A snapshot of the current evidence. *Explore (NY)*, 15(6), 434–439. doi.org/10.1016/j.explore.2019.08.009.
- [8] Han, J. S., Ding, X. Z., & Fan, S. G. (1986). Cholecystokinin octapeptide (CCK-8): Antagonism to electroacupuncture

- analgesia and a possible role in electroacupuncture tolerance. *Pain*, 27(1), 101-115. doi: 10.1016/0304-3959(86)90227-7.
- [9] Lin, J., & Chen, W. (2008). Acupuncture Analgesia: A Review of Its Mechanisms of Actions. *The American Journal of Chinese Medicine*, 36(4), 635-645. doi.org/10.1142/S0192415X08006107.
- [10] Wang, S., Kain, Z.N., & White, P. (2008). Acupuncture Analgesia: I. The Scientific Basis. *Anesthesia & Analgesia*, 106(2), 602-610. doi: 10.1213/01.ane.0000277493.42335.7b.
- [11] Cheng, R.S., & Pomeranz, B. (1979). Electroacupuncture analgesia could be mediated by at least two pain relieving mechanisms: endorphin and non-endorphin systems. *Life Sciences*, 25(23), 1957-1962. doi.org/10.1016/0024-3205(79)90598-8.
- [12] Tsai, H.Y., Chen, Y.F. & Lin, J.G. (1989). Effect of electroacupuncture analgesia on serotonergic neurons in rat central nervous system. *Chinese Journal of Clinical Pharmacology*, 41, 123-126.
- [13] Millan, M.J. (2002). Descending control of pain. *Progress in Neurobiology*, 66(6), 355-474. doi.org/10.1016/S0301-0082(02)00009-6.
- [14] Goldman, N., Chen, M., Fujita, T., et al. (2010). Adenosine A1 receptors mediate local anti-nociceptive effects of acupuncture. *Nature Neuroscience*, 13(7), 883-888.
- [15] Yim, Y.K., Lee, H., Hong, K.E., et al. (2007). Electro-acupuncture at acupoint ST36 reduces inflammation and regulates immune activity in collagen-induced arthritic mice. *Evidence-Based Complementary and Alternative Medicine*, 4, 51-57. doi.org/10.1093/ecam/nel054.
- [16] Yu, Y., Kasahara, T., Sato, T., et al. (1998). Role of endogenous interferon- γ on the enhancement of splenic NK cell activity by electroacupuncture stimulation in mice. *Journal of Neuroimmunology*, 90(2), 176-186. doi.org/10.1016/S0165-5728(98)00143-X.
- [17] Jin, B.X., Jin, L.L., & Jin, G. (2019). The anti-inflammatory effect of acupuncture and its significance in analgesia. *World Journal of Acupuncture - Moxibustion*, 29(1), 1-6. doi.org/10.1016/j.wjam.2019.03.003.
- [18] Chiang, C.Y., Li, Z., Dostrovsky, J.O., et al. (2008). Glutamine uptake contributes to central sensitization in the medullary dorsal horn. *NeuroReport*, 19(11), 1151-1154. doi: 10.1097/WNR.0b013e3283086781.
- [19] Sun, R.Q., Wang, H.C., Wan, Y., et al. (2004). Suppression of neuropathic pain by peripheral electrical stimulation in rats: μ -opioid receptor and NMDA receptor implicated. *Experimental Neurology*, 187(1), 23-29. doi.org/10.1016/j.expneurol.2003.12.011.
- [20] Choi, B.T., Kang, J., & Jo, U.B. (2005). Effects of electroacupuncture with different frequencies on spinal ionotropic glutamate receptor expression in complete Freund's adjuvant-injected rat. *Acta Histochemica*, 107(1), 67-76. doi.org/10.1016/j.acthis.2004.07.008.
- [21] Xing, G., Liu, F., Qu, X., et al. (2007). Long-term synaptic plasticity in the spinal dorsal horn and its modulation by electroacupuncture in rats with neuropathic pain. *Experimental Neurology*, 208(2), 323-332. doi.org/10.1016/j.expneurol.2007.09.004.
- [22] Nielsen, A., Dusek, J., Taylor-Swanson, L., et al. (2022). Acupuncture Therapy as an Evidence-Based Nonpharmacologic Strategy for Comprehensive Acute Pain Care: The Academic Consortium Pain Task Force White Paper Update. *Pain Medicine*, 23(9), 1582-1612. doi.org/10.1093/pm/pnac056.
- [23] Baroncini, A., Maffulli, N., Eschweiler, J., et al. (2022). Acupuncture in chronic aspecific low back pain: a Bayesian network meta-analysis. *Journal of Orthopaedic Surgery and Research*, 17, 319. doi.org/10.1186/s13018-022-03212-3.
- [24] Haake, M., Müller, H., Schade-Brittinger, C., et al. (2007). German Acupuncture Trials (Gerac) For Chronic Low Back Pain: Randomized, Multicenter, Blinded, Parallel-Group Trial With 3 Groups. *JAMA Internal Medicine*, 167(17), 1892-1898. doi:10.1001/Archinte.167.17.1892.
- [25] Manheimer, E., Cheng, K., Linde, K., et al. (2010). Acupuncture for peripheral joint osteoarthritis. *Cochrane Database of Systematic Reviews*, (1), CD001977. doi.org/10.1002/14651858.CD001977.pub2.
- [26] Fang, J., Shi, H., Wang, W. et al. (2024). Durable Effect of Acupuncture for Chronic Neck Pain: A Systematic Review and Meta-Analysis. *Current Pain and Headache Reports*, 28, 957-969. doi.org/10.1007/s11916-024-01267-x.

- [27] Linde,K., Allais,G., Brinkhaus, B., et al. (2016). Acupuncture for the prevention of episodic migraine. Cochrane Database of Systematic Reviews, (6), CD001218. doi.org/10.1002/14651858.CD001218.pub3.
- [28] Linde,K., Allais,G., Brinkhaus, B., et al. (2016). Acupuncture for the prevention of tension-type headache. Cochrane Database of Systematic Reviews, (4), CD007587. doi.org/10.1002/14651858.CD007587.pub2.
- [29] Crawford,P., Penzien,D.B., & Coeytaux,R. (2017). Reduction in Pain Medication Prescriptions and Self-Reported Outcomes Associated with Acupuncture in a Military Patient Population. Medical Acupuncture, 29(4), 229-231. doi.org/10.1089/acu.2017.1234.
- [30] Shah,S., Godhardt,L., & Spofford,C. (2022). Acupuncture and Postoperative Pain Reduction. Current Pain and Headache Reports, 26, 453-458. doi.org/10.1007/s11916-022-01048-4.
- [31] Zheng,Z., Guo,RJ., Helme,RD., et al. (2008). The effect of electroacupuncture on opioid-like medication consumption by chronic pain patients: a pilot randomized controlled clinical trial. European Journal of Pain, 12(5), 671-676. doi.org/10.1016/j.ejpain.2007.10.003.
- [32] He, Y., Guo, X., May, BH., et al. (2020). Clinical Evidence for Association of Acupuncture and Acupressure With Improved Cancer Pain: A Systematic Review and Meta-Analysis. JAMA Oncology, 6(2), 271-278. doi:10.1001/jamaoncol.2019.5233.
- [33] Lu,L., Chen, C., Chen,Y., et al. (2024). Effect of Acupuncture for Methadone Reduction: A Randomized Clinical Trial. Annals of Internal Medicine, 177(8), 1039-1047. doi.org/10.7326/M23-2721.
- [34] Bäumlér,P., Zhang,W., Stübinger,T., et al. (2021). Acupuncture- related adverse events: systematic review and meta-analyses of prospective clinical studies. BMJ Open, 11(9), e045961. doi: 10.1136/bmjopen-2020-045961.

A Review of Postoperative Outcomes and Complication Management in Cataract Surgery

DengFeng Wang*

Third Division General Hospital, Xinjiang Production and Construction Corps, Xinjiang, 843999, China

*Corresponding author: DengFeng Wang

Copyright: 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY-NC 4.0), permitting distribution and reproduction in any medium, provided the original author and source are credited, and explicitly prohibiting its use for commercial purposes.

Abstract: Cataract is the leading cause of reversible blindness worldwide, affecting millions, particularly the elderly. Over 65 million people suffer from significant visual impairment due to cataracts, with the burden being highest in low- and middle-income countries where access to surgery is limited. Cataract surgery, one of the most commonly performed and cost-effective procedures, has evolved significantly. Traditional extracapsular cataract extraction (ECCE) has been largely replaced by phacoemulsification, which uses ultrasonic energy through a small incision, reducing recovery time and complications. More recently, femtosecond laser-assisted cataract surgery (FLACS) has emerged, offering enhanced precision but with ongoing evaluation of its cost-effectiveness. Intraocular lenses (IOLs) now allow for customized visual outcomes, addressing distance, near, and intermediate vision. Despite its safety, cataract surgery can still result in complications such as corneal edema and posterior capsular opacification, requiring careful surgical management and patient education.

Keywords: Cataract; Phacoemulsification; Femtosecond Laser; Intraocular Lens; Postoperative Complications

Published: Jan 20, 2026

DOI: <https://doi.org/10.62177/apjcmr.v2i1.1055>

1.Introduction

Cataract remains the leading cause of reversible blindness worldwide, affecting millions of individuals across diverse age groups and socioeconomic backgrounds. Globally, it is estimated that over 65 million people suffer from significant visual impairment due to cataract, with the prevalence increasing sharply among the elderly population. The burden of cataract is particularly pronounced in low- and middle-income countries, where access to timely surgical intervention is often limited, resulting in prolonged visual disability and reduced quality of life. Beyond visual impairment, cataracts impose considerable socioeconomic costs, including loss of productivity, increased dependence on caregivers, and heightened risk of accidents. Consequently, cataract surgery has emerged as one of the most commonly performed and cost-effective procedures in modern ophthalmology, providing substantial improvements in both vision and overall patient well-being ^[1].

Over the past few decades, cataract surgery has undergone significant evolution, driven by advances in technology, surgical instrumentation, and understanding of ocular physiology. Traditionally, extracapsular cataract extraction (ECCE) was the mainstay procedure, requiring a relatively large incision and extended recovery time. The advent of phacoemulsification revolutionized cataract surgery by allowing fragmentation and removal of the crystalline lens through a small, self-sealing incision using ultrasonic energy ^[2]. This approach not only reduces intraoperative trauma but also accelerates postoperative visual recovery and decreases the risk of complications such as corneal edema and wound leakage. More recently, femto-

second laser-assisted cataract surgery (FLACS) has emerged as a cutting-edge technique, enabling highly precise corneal incisions, capsulotomy, and lens fragmentation through computer-guided laser systems. By enhancing reproducibility and reducing manual variability, FLACS offers potential advantages in visual outcomes and complication mitigation, although its cost-effectiveness compared with conventional phacoemulsification continues to be evaluated.

Central to modern cataract surgery is the implantation of intraocular lenses (IOLs), which not only restore refractive function but also allow customization of visual outcomes. Advances in IOL technology, including aspheric designs, multifocal optics, toric correction for astigmatism, and extended depth-of-focus lenses, have dramatically expanded the scope of cataract surgery from mere lens extraction to functional visual rehabilitation. These innovations have shifted patient expectations, with many individuals seeking not only restoration of distance vision but also enhanced near and intermediate vision for daily activities. Consequently, the preoperative evaluation, surgical planning, and IOL selection process have become increasingly critical in optimizing postoperative outcomes and patient satisfaction ^[3].

While cataract surgery is generally considered safe and effective, postoperative outcomes and complication management remain crucial aspects of clinical practice. Despite technological advancements, complications such as corneal edema, intraocular pressure elevation, posterior capsular opacification, cystoid macular edema, and, in rare cases, endophthalmitis, can significantly impact visual recovery and quality of life. Early identification of risk factors, meticulous surgical technique, and proactive management strategies are essential to minimize adverse events and ensure optimal functional outcomes ^[4]. Furthermore, patient education regarding postoperative care, including adherence to topical medications, recognition of warning signs, and timely follow-up visits, plays a vital role in preventing and managing complications. In the context of an aging population and increasing surgical volume, systematic assessment of postoperative outcomes has become an essential component of evidence-based ophthalmic practice.

To facilitate comprehensive understanding of the diverse cataract surgery techniques, Table 1 summarizes key parameters of commonly performed procedures, including incision size, anesthesia type, and typical surgery duration. This overview highlights the evolution of surgical approaches from traditional extracapsular extraction to modern laser-assisted and phacoemulsification techniques, underscoring the trend toward minimally invasive procedures with enhanced safety and efficacy ^[5]. By establishing a clear framework of surgical options, clinicians can better tailor interventions to individual patient needs, balancing procedural complexity, anticipated visual outcomes, and potential risk of complications.

In summary, cataract surgery represents a cornerstone of modern ophthalmology, offering profound improvements in vision, function, and quality of life for millions of patients worldwide. Continuous innovation in surgical techniques, lens technology, and perioperative management has expanded the scope of achievable outcomes, yet the careful evaluation of postoperative results and vigilant complication management remain central to clinical success ^[6]. Understanding the interplay between surgical methodology, patient characteristics, and postoperative care is essential for optimizing outcomes and advancing the field toward increasingly safe, precise, and patient-centered cataract interventions.

Table 1. Overview of Common Cataract Surgery Techniques and Key Surgical Parameters

Surgical Technique	Incision Size (mm)	Anesthesia Type	Typical Surgery Duration (min)
Extracapsular Cataract Extraction	8–10	Local or General	30–60
Phacoemulsification	2–3	Topical/Local	10–20
Femtosecond Laser-Assisted Surgery	2–3	Topical/Local	15–25

2. Postoperative Visual Outcomes

Postoperative visual outcomes remain the paramount measure of success in cataract surgery, serving as both an objective indicator of surgical efficacy and a patient-centered benchmark for satisfaction. Visual outcomes encompass multiple parameters, including best-corrected visual acuity (BCVA), uncorrected visual acuity (UCVA), and refractive status, all of which are routinely assessed during follow-up visits.

2.1 Visual Assessment Metrics and Methodology

Measurement of visual acuity typically relies on standardized charts, such as the Snellen or Early Treatment Diabetic

Retinopathy Study (ETDRS) charts, providing a quantifiable assessment of distance vision. Refractive outcomes, including residual spherical and cylindrical errors, are evaluated through manifest or automated refraction techniques. In specialized centers, advanced metrics such as higher-order aberrations and contrast sensitivity are also assessed [7]. These metrics collectively provide a comprehensive evaluation of visual function, guiding postoperative care and informing patient counseling.

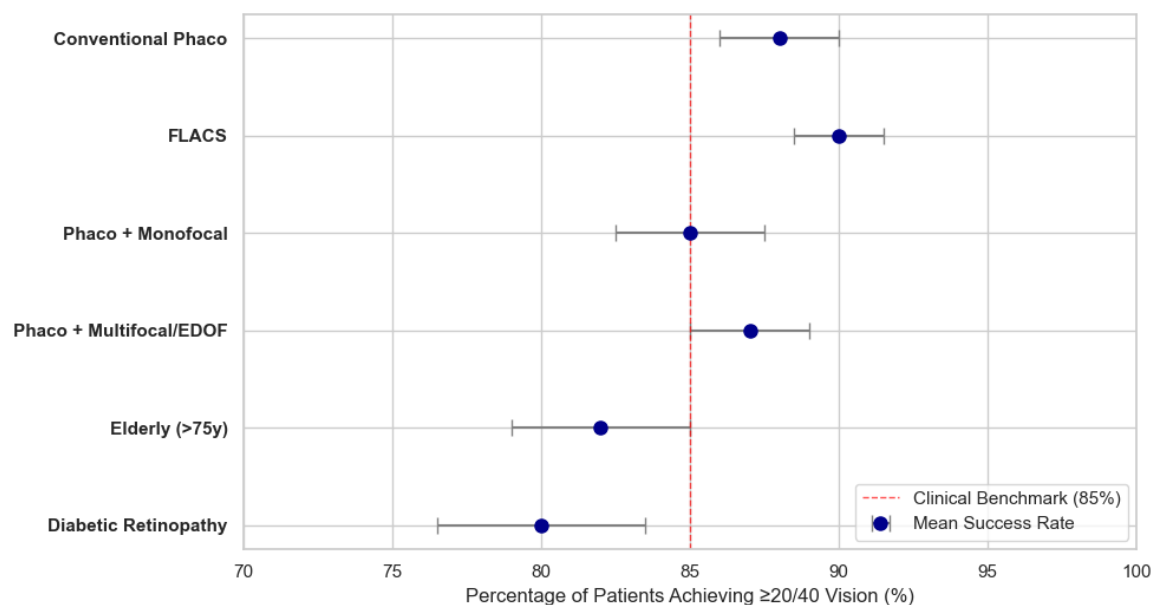
2.2 Clinical Data on Visual Improvement

The improvement in visual acuity following cataract surgery is substantial. Clinical data indicates that the majority of patients achieve 20/40 vision or better within a few weeks postoperatively. Early studies reported that conventional phacoemulsification yields a mean BCVA improvement of approximately 3–4 lines on the Snellen chart, with nearly 85–90% of patients attaining 20/40 vision or better.

Recent innovations, including femtosecond laser-assisted surgery (FLACS) and advanced intraocular lens (IOL) designs, have further enhanced visual outcomes by minimizing surgically induced astigmatism and improving optical quality. Multifocal and extended depth-of-focus (EDOF) IOLs allow simultaneous correction of distance and near vision, providing functional visual independence [8].

Figure 1 illustrates the comparative efficacy of these techniques. As shown, while conventional methods are highly effective, advanced modalities like FLACS and EDOF IOLs push the ceiling of visual rehabilitation higher.

Figure 1: Comparative Visual Rehabilitation Success Rates (Forest Plot Analysis of Clinical Subgroups)



2.3 Factors Influencing Visual Recovery

Postoperative visual recovery is multifactorial, encompassing patient-specific, ocular, and surgical variables. Understanding these variables enables ophthalmologists to stratify risk and tailor perioperative care. Table 2 classifies these key determinants.

Table 2. Classification of Key Risk Factors Affecting Postoperative Visual Recovery

Factor Category	Specific Variables	Potential Impact on Prognosis
Demographic	Advanced Age (>75 years)	Slower corneal endothelial recovery; delayed neural adaptation.
Systemic	Diabetes Mellitus, Hypertension	Increased risk of cystoid macular edema; exacerbated inflammation.
Ocular Comorbidity	Glaucoma, AMD, Diabetic Retinopathy	Limits maximum potential BCVA; affects contrast sensitivity.
Surgical	High Phaco Energy, Prolonged Duration	Induces corneal edema, delaying early visual rehabilitation.
IOL-Related	Decentration, Tilt	Induces higher-order aberrations (coma), reducing visual quality.

2.4 Patient-Reported Outcomes (PROs) and Quality of Life

Patient-reported outcomes (PROs) and quality of life (QoL) have emerged as essential complements to traditional acuity measurements. Standardized questionnaires, such as the NEI VFQ-25 and Catquest-9SF, allow for the quantification of patient satisfaction. Studies consistently demonstrate that cataract surgery results in significant improvements in vision-related quality of life. Notably, the correlation between objective visual acuity and PROs is not always linear; some patients with modest BCVA gains experience substantial quality-of-life improvements ^[9].

2.5 Comparative Analysis of Techniques and Demographics

Comparative analysis reveals nuances in effectiveness across different approaches. Conventional phacoemulsification remains highly effective with a predictable safety profile. However, Femtosecond laser-assisted cataract surgery (FLACS) has been shown to achieve comparable or slightly superior refractive outcomes, particularly regarding capsulotomy centration.

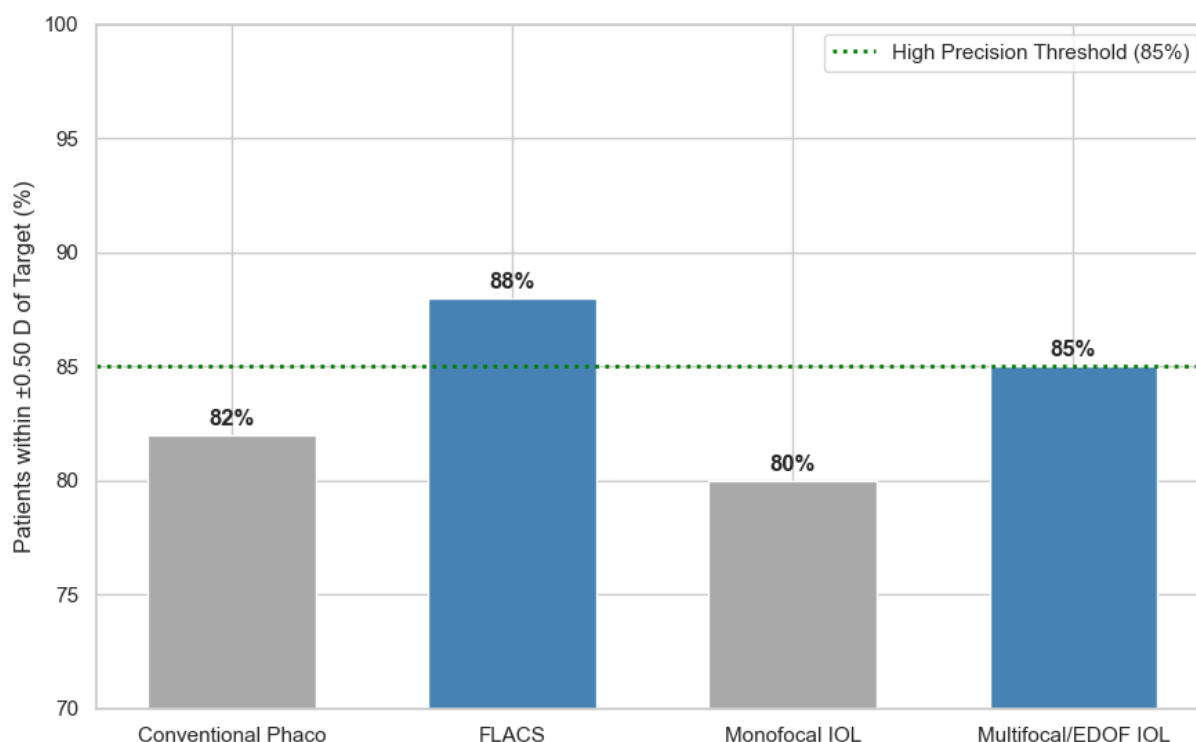
Table 3 summarizes the postoperative visual outcomes across different surgical techniques and patient subgroups, highlighting the refractive precision advantage of modern techniques.

Table 3. Summary of Postoperative Visual Outcomes by Surgical Technique and Patient Group

Patient Group / Technique	Mean BCVA Improvement (Snellen lines)	% Achieving 20/40 Vision	% Within ± 0.50 D of Target (Refractive Accuracy)
Conventional Phacoemulsification	3.5	88%	82%
Femtosecond Laser-Assisted (FLACS)	3.6	90%	88%
Phaco + Monofocal IOL	3.4	85%	80%
Phaco + Multifocal/EDOF IOL	3.7	87%	85%
Elderly Patients (>75 years)	3.2	82%	78%
Mild Diabetic Retinopathy	3.1	80%	75%

Figure 2 visualizes the “Refractive Precision” data from Table 2. The chart demonstrates that FLACS and Premium IOLs provide a tighter distribution of outcomes around the refractive target, reducing the need for postoperative spectacle correction.

Figure 2: Refractive Predictability by Surgical Modality



3. Early Postoperative Complications

Early postoperative complications in cataract surgery are defined as adverse events occurring within the first month following the procedure. Despite the remarkable safety and efficacy of modern cataract surgery, these early complications can significantly affect visual recovery and patient satisfaction. The incidence varies based on surgical technique and patient risk profiles, ranging from minor, self-limiting issues to events requiring intervention.

3.1 Corneal Edema

Corneal edema is a frequent early complication, typically appearing within the first few days post-surgery. It primarily results from transient endothelial dysfunction or mechanical trauma from phacoemulsification energy.

Clinical Presentation: Diffuse stromal haze, increased central corneal thickness (CCT), and reduced visual acuity.

Incidence: 2% to 15%, with higher rates in dense cataracts or patients with Fuchs' dystrophy.

Management: Topical hyperosmotic agents (e.g., 5% Sodium Chloride), corticosteroids, and IOP control. Severe, persistent cases may require endothelial keratoplasty (DSEK/DMEK).

3.2 Anterior Chamber Inflammation (Postoperative Uveitis)

Characterized by cells and flare in the anterior chamber, this condition results from surgical trauma or retained lens material.

Incidence: Clinically significant inflammation occurs in 1–5% of patients.

Risk Factors: History of uveitis, diabetes mellitus, or intraoperative complications like posterior capsule rupture.

Prophylaxis & Treatment: Meticulous aseptic technique and intracameral antibiotics. Treatment involves a tapering course of topical corticosteroids or NSAIDs over 2–4 weeks.

3.3 Elevated Intraocular Pressure (IOP)

Transient IOP spikes are common in the first 24–48 hours, often caused by retained viscoelastic material (OVD) or inflammatory debris.

Incidence: 5% to 15% of cases experience a significant spike.

High-Risk Groups: Patients with pre-existing glaucoma, shallow anterior chambers, or those receiving high-viscosity OVDs.

Management Protocol:

First Line: Topical beta-blockers, alpha-agonists, or carbonic anhydrase inhibitors.

Refractory: Anterior chamber paracentesis ("burping" the wound) to release fluid.

Figure 4 below provides a clinical decision flowchart for managing postoperative IOP spikes.

(See Figure 4 in the "Generated Charts" section below)

3.4 Early Posterior Capsular Opacification (PCO)

While typically a late complication, early PCO can develop within the first month due to rapid proliferation of residual lens epithelial cells.

Prevention: 360-degree cortical cleanup and use of square-edged IOLs to create a barrier effect.

Treatment: If visually significant, Nd:YAG laser capsulotomy is the gold standard, though usually deferred until the eye is quiet.

3.5 Comparative Incidence and Risk Profile

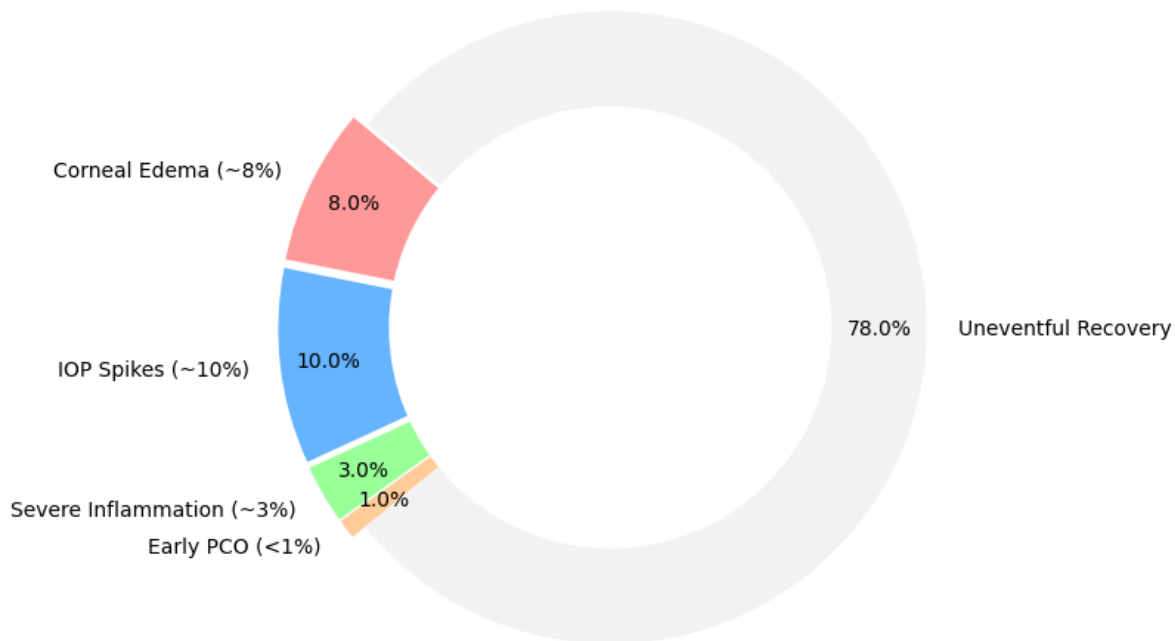
To provide a clear overview of the clinical landscape, Table 4 summarizes the key characteristics of these complications.

Table 4. Summary of Early Postoperative Complications: Incidence, Risk Factors, and Management

Complication	Estimated Incidence	Primary Risk Factors	First-Line Management
Corneal Edema	2% – 15%	High Phaco Energy, Fuchs' Dystrophy, Dense Cataract	Hypertonic Saline, Steroids
IOP Spike (>30 mmHg)	5% – 15%	Retained Viscoelastic, Glaucoma, Shallow Chamber	Topical IOP-lowering drops, Paracentesis
Severe Inflammation (Uveitis)	1% – 5%	Diabetes, Hx of Uveitis, Long Surgery Duration	Intensive Topical Steroids, NSAIDs
Early PCO	< 1% (Early)	Cortical Remnants, Rounded-edge IOLs	Observation, YAG Laser (delayed)

Figure 3 visually represents the relative frequency of these complications, highlighting Corneal Edema and IOP Spikes as the most common issues to anticipate.

Figure 3: Relative Incidence of Early Postoperative Events



3.6 Preventive Strategies and Clinical Guidelines

Preventive measures have evolved to address these risks effectively. International guidelines emphasize:

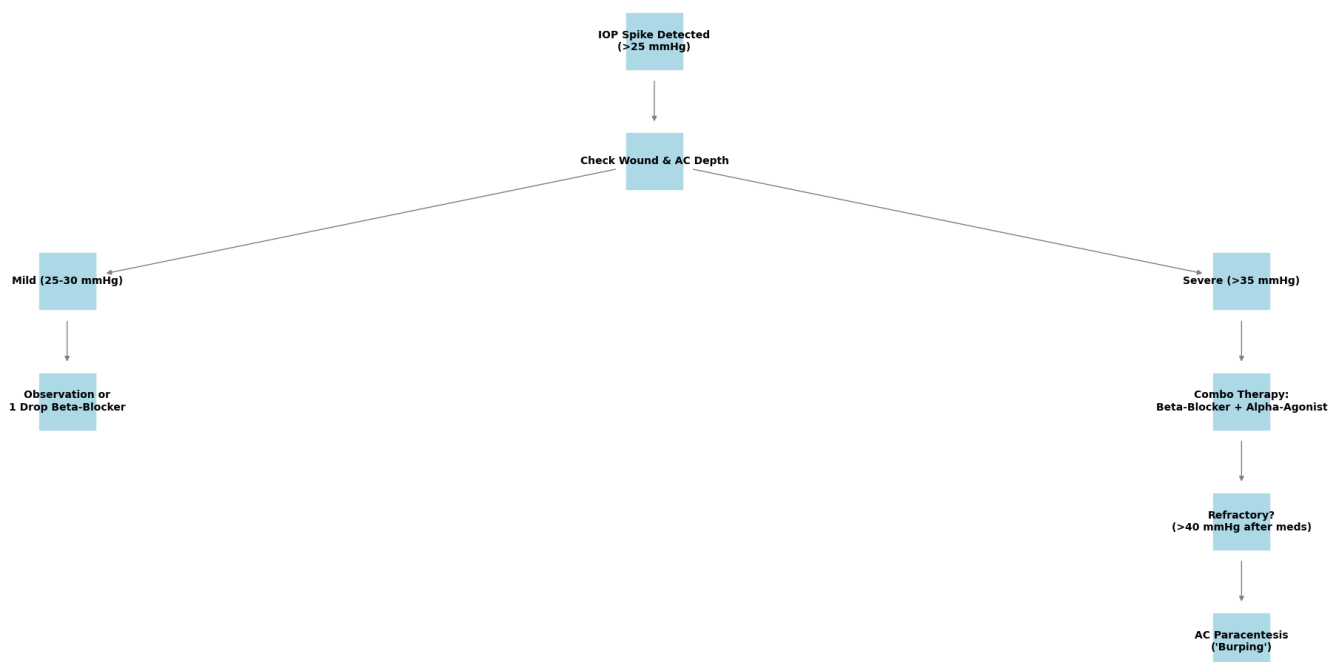
Preoperative: Optimization of systemic conditions (e.g., blood sugar control in diabetics).

Intraoperative: Use of “Soft-Shell” techniques with viscoelastics to protect the endothelium.

Postoperative: Standardized follow-up at 1 day, 1 week, and 1 month.

Early postoperative complications, while generally manageable, require vigilant monitoring. By understanding the risk profiles summarized in Table 4 and adhering to the management protocols illustrated in Figure 4, ophthalmologists can minimize morbidity and ensure optimal visual rehabilitation.

Figure 4: Clinical Algorithm for Managing Postoperative IOP Elevation



4. Late Postoperative Complications

Late postoperative complications in cataract surgery are defined as adverse events manifesting beyond one month following the procedure. While modern cataract surgery is characterized by high safety profiles, these delayed events can significantly compromise long-term visual rehabilitation and ocular health^[10]. Although generally less frequent than early complications, late events often necessitate specialized intervention, ranging from laser procedures to complex vitreoretinal surgery.

4.1 Posterior Capsular Opacification (PCO)

PCO, often termed “secondary cataract,” remains the most prevalent late complication. It results from the proliferation and migration of residual lens epithelial cells (LECs) across the posterior capsule visual axis.

Incidence & Kinetics: Reported rates range from 10% to 50% within 2–5 years post-surgery. The risk curve is steepest in younger patients and those with hydrophilic acrylic lenses.

Preventive Architecture: The use of IOLs with a sharp, square posterior edge creates a mechanical barrier against LEC migration.

Management: Nd:YAG laser capsulotomy is the gold standard intervention, effectively restoring visual clarity in >95% of cases^[11].

4.2 Pseudophakic Cystoid Macular Edema (Irvine-Gass Syndrome)

CME involves fluid accumulation in the outer plexiform and inner nuclear layers of the macula, detectable via Optical Coherence Tomography (OCT).

Temporal Pattern: Peak incidence occurs 4–12 weeks postoperatively.

Risk Profile: Incidence is 1–5% in uncomplicated cases but spikes significantly in patients with diabetic retinopathy, vein occlusions, or history of uveitis.

Therapeutic Strategy: First-line treatment involves topical NSAIDs and corticosteroids. Refractory cases may require periocular steroid injections or intravitreal anti-VEGF agents^[12].

4.3 Late IOL Dislocation

Late in-the-bag IOL dislocation is a progressive complication caused by zonular dehiscence or capsular bag contraction.

Incidence: 0.1%–1.0%, though increasing due to the aging population.

Key Driver: Pseudoexfoliation Syndrome (PXF) is the leading cause, alongside prior trauma and connective tissue disorders (e.g., Marfan syndrome).

Intervention: Management depends on severity, ranging from observation to scleral-fixated IOL exchange^[13].

4.4 Delayed-Onset Endophthalmitis

Chronic endophthalmitis is a rare but sight-threatening condition, often caused by sequestered, low-virulence organisms like *Cutibacterium acnes* (formerly *P. acnes*) within the capsular bag^[14].

Presentation: Persistent, low-grade anterior chamber inflammation (often misdiagnosed as non-infectious uveitis) appearing months after surgery.

Management: Requires microbiological sampling and may necessitate partial or total capsulectomy with IOL removal and intravitreal antibiotics^[15,16].

4.5 The “Risk Landscape”: A Topographic Analysis

To visualize the complex relationship between the timing of these complications and their clinical impact, we present a Risk Topography Map (Figure 5). This advanced visualization treats risk as a “terrain,” where elevation represents the frequency of the event, and the X-Y coordinates represent time and severity.

4.6 Summary of Clinical Data

Table 5 synthesizes the incidence, risk factors, and management protocols for these late-stage events.

Figure 5: Postoperative Risk Topography Mapping Complications by Time, Severity, and Frequency

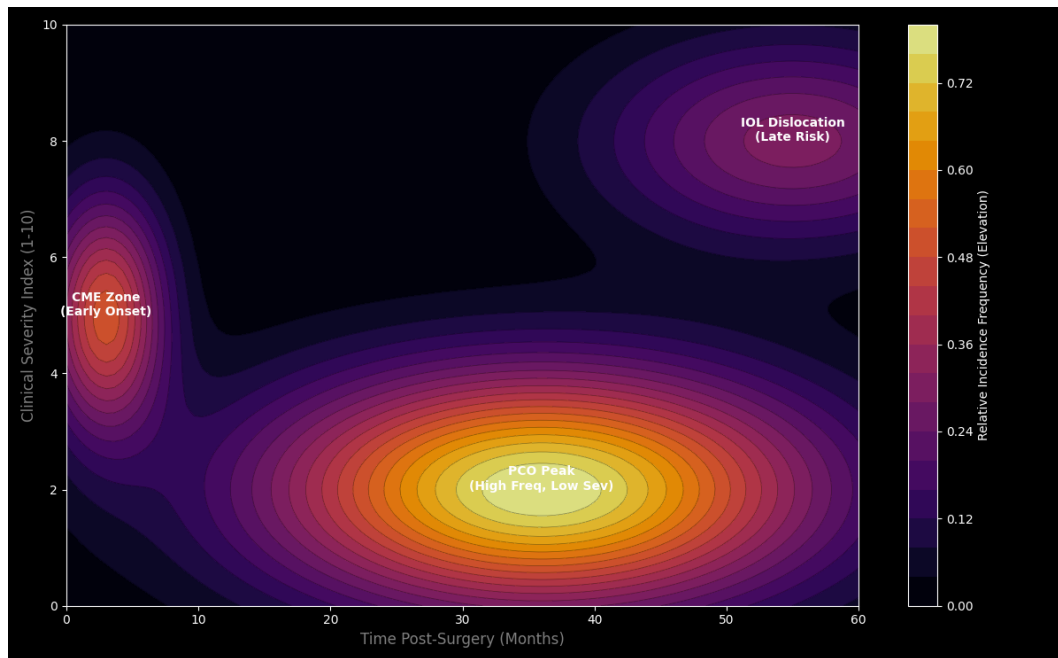


Table 5. Late Postoperative Complications: Clinical Profile Matrix

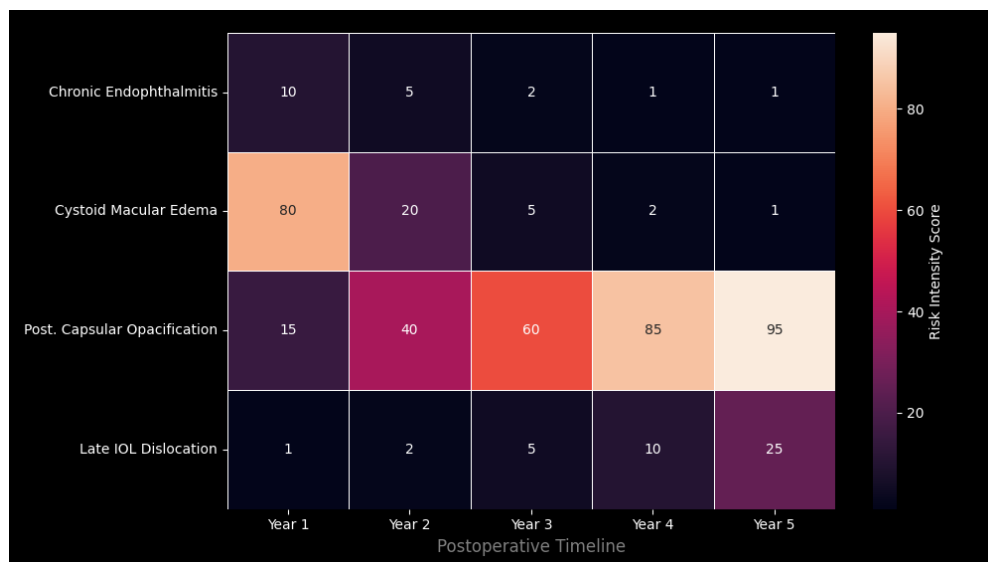
Complication	Onset Window	Incidence (5-Year)	Primary Risk Factors	Standard Management
PCO	Months to Years	10% – 50%	Young Age, Round-edge IOLs	Nd:YAG Laser Capsulotomy
Cystoid Macular Edema	1 – 3 Months	1% – 5%	Diabetes, Uveitis, Vitreous Loss	Topical NSAIDs + Steroids
Late IOL Dislocation	Years	0.1% – 1%	Pseudoexfoliation, Trauma	Surgical Repositioning/Exchange
Chronic Endophthalmitis	1 – 9 Months	0.01% – 0.1%	Sequestration of P. acnes	Vitrectomy + IOL Removal

4.7 Conclusion and Long-Term Surveillance

In summary, late postoperative complications pose significant challenges to long-term visual stability. While PCO is the most common and easily treatable, conditions like IOL dislocation and chronic endophthalmitis require high clinical vigilance. As illustrated in the Risk Heatmap (Figure 6), the “danger zones” for these complications vary significantly over time.

Preventive strategies—ranging from precise biometry to the selection of square-edged IOLs—combined with patient education on warning signs (e.g., flashing lights, drop in vision), remain the cornerstones of long-term success^[17].

Figure 6: Temporal Risk Evolution Heatmap



5. Advances in Complication Prevention and Management

The continuous evolution of cataract surgery has not only enhanced visual outcomes but also significantly reduced the incidence and severity of postoperative complications. Advances in surgical techniques, pharmacological interventions, postoperative monitoring, and patient education have collectively transformed the management of both early and late complications. This section provides a comprehensive overview of current innovations aimed at preventing complications and optimizing patient care ^[18].

Innovations in surgical techniques represent the cornerstone of complication prevention in modern cataract surgery. The transition from traditional extracapsular cataract extraction (ECCE) to phacoemulsification and small-incision surgery has reduced tissue trauma, accelerated visual recovery, and minimized early complications such as corneal edema and anterior chamber inflammation. Small-incision surgery, typically involving a 2–3 mm self-sealing corneal incision, reduces surgically induced astigmatism and preserves the integrity of the ocular surface ^[19]. Furthermore, the introduction of femtosecond laser-assisted cataract surgery (FLACS) has enhanced the precision of corneal incisions, capsulotomy, and lens fragmentation. By providing consistent, reproducible capsulotomy diameter and centration, FLACS reduces the risk of intraocular lens (IOL) decentration and posterior capsular opacification ^[20]. Additionally, intraoperative guidance systems, such as real-time optical coherence tomography and image-guided toric IOL alignment, further minimize human error, improving both refractive predictability and safety.

Pharmacological strategies play a pivotal role in mitigating both early and late postoperative complications. The judicious use of anti-inflammatory agents, including corticosteroids and nonsteroidal anti-inflammatory drugs (NSAIDs), has been shown to reduce anterior chamber inflammation, prevent cystoid macular edema, and limit postoperative pain ^[21]. Topical corticosteroids, administered in tapering regimens, remain the standard for controlling postoperative inflammation, whereas NSAIDs serve as adjuncts to enhance prophylaxis against macular edema and provide analgesic benefits. Anti-infective prophylaxis is also critical in minimizing the risk of postoperative endophthalmitis. Intracameral antibiotics, such as cefuroxime or moxifloxacin, administered at the conclusion of surgery, have demonstrated superior efficacy in reducing infection rates compared to topical therapy alone. In addition, preoperative antiseptic preparation with povidone-iodine and maintenance of sterile operative conditions remain essential components of infection prevention ^[22].

Postoperative monitoring protocols and follow-up schedules are central to early detection and timely management of complications. Standardized follow-up often includes examinations at 1 day, 1 week, 1 month, and 3 months postoperatively, with additional visits based on patient-specific risk factors. Early postoperative visits focus on detecting corneal edema, anterior chamber inflammation, elevated intraocular pressure, and wound integrity, while later visits assess posterior capsular opacification, cystoid macular edema, and IOL stability. Incorporation of advanced imaging modalities, such as optical coherence tomography (OCT), corneal pachymetry, and endothelial cell counts, allows for objective evaluation of subtle structural changes, facilitating early intervention. Teleophthalmology and remote monitoring systems are emerging as adjuncts to conventional follow-up, particularly for patients in rural or underserved areas, enhancing adherence and enabling prompt identification of visual disturbances ^[23].

Patient education and adherence strategies are equally vital in reducing postoperative complications. Educating patients on the correct use of topical medications, the importance of hygiene, and the recognition of warning signs—such as sudden visual loss, pain, or photophobia—can dramatically improve outcomes. Written instructions, demonstration of drop instillation techniques, and reinforcement through follow-up calls or digital platforms have been shown to increase adherence and reduce preventable complications. Patient engagement in self-monitoring, including awareness of visual fluctuations and timely reporting of symptoms, complements clinical surveillance and enables early intervention ^[24].

Integration of evidence-based management algorithms further streamlines the approach to postoperative complications. By linking specific complications with preventive measures and therapeutic strategies, ophthalmologists can ensure consistent and efficient care. For example, corneal edema can be mitigated by minimizing phacoemulsification energy and using protective viscoelastic substances, with treatment consisting of hypertonic saline, corticosteroids, or, in severe cases, surgical intervention. Elevated intraocular pressure can be prevented by thorough viscoelastic removal and controlled anterior

chamber maintenance, with management including topical or systemic IOP-lowering agents. Posterior capsular opacification is minimized by employing square-edged IOLs and meticulous cortical cleanup, with Nd:YAG laser capsulotomy serving as definitive treatment when necessary. Cystoid macular edema prevention relies on perioperative anti-inflammatory therapy, with escalation to intravitreal injections in refractory cases ^[25]. Endophthalmitis prevention emphasizes strict asepsis and prophylactic antibiotics, with intensive medical therapy or vitrectomy for established infection.

Table 3 provides a structured overview of recommended management algorithms for common postoperative complications, illustrating the relationship between complication, preventive measures, and treatment options. Such a framework enables clinicians to anticipate potential issues, implement targeted interventions, and maintain a high standard of care across diverse patient populations ^[26].

Table 3. Recommended Management Algorithms for Common Postoperative Complications

Complication	Prevention Strategies	Treatment Approaches
Corneal Edema	Minimize phaco energy, use viscoelastic agents	Hypertonic saline, topical corticosteroids, surgery if severe
Anterior Chamber Inflammation	Gentle manipulation, prophylactic NSAIDs/corticosteroids	Topical corticosteroids, monitor IOP
Elevated IOP	Complete viscoelastic removal, maintain anterior chamber	Topical/systemic IOP-lowering medications, paracentesis if needed
Posterior Capsular Opacification	Square-edged IOLs, cortical cleanup	Nd:YAG laser capsulotomy
Cystoid Macular Edema	Perioperative NSAIDs/corticosteroids	Topical/ periocular corticosteroids, intravitreal injections if refractory
Endophthalmitis	Aseptic technique, intracameral antibiotics	Intensive topical/systemic antibiotics, vitrectomy if severe

In recent years, the combination of technological innovation, pharmacological prophylaxis, structured monitoring, and patient-centered education has significantly improved the safety profile of cataract surgery ^[27]. Emerging strategies, such as minimally invasive microincision cataract surgery, advanced IOL materials resistant to opacification, and digital adherence tools, promise further reductions in postoperative complications. Moreover, ongoing research into the molecular mechanisms underlying cystoid macular edema, endothelial cell loss, and posterior capsular opacification may inform future preventive and therapeutic approaches, leading to increasingly personalized cataract care .

6. Conclusions and Future Perspectives

Cataract surgery has evolved into one of the safest and most effective surgical procedures worldwide, offering significant improvements in visual acuity, functional vision, and quality of life. This review highlights several key findings from the current literature regarding postoperative outcomes and complication management. Advances in surgical techniques, including phacoemulsification, small-incision surgery, and femtosecond laser-assisted procedures, have enhanced precision, minimized intraoperative trauma, and reduced the incidence of both early and late complications. The development of innovative intraocular lens (IOL) designs, such as multifocal, toric, and extended depth-of-focus lenses, has further expanded the scope of achievable visual rehabilitation, enabling patients to attain functional vision across multiple distances with greater spectacle independence. Moreover, the integration of pharmacological prophylaxis, including anti-inflammatory and anti-infective agents, has proven effective in preventing anterior chamber inflammation, cystoid macular edema, and postoperative endophthalmitis, thereby improving patient safety and satisfaction.

Despite these advancements, postoperative complications remain a relevant concern. Early complications such as corneal edema, elevated intraocular pressure, and anterior chamber inflammation continue to occur, albeit at reduced rates, while late complications including posterior capsular opacification, cystoid macular edema, lens dislocation, and delayed endophthalmitis can impact long-term visual outcomes. Risk factors for these complications are multifactorial, encompassing patient-specific variables (age, systemic comorbidities, ocular pathology), surgical factors (technique, intraoperative complexity), and postoperative adherence to therapy and follow-up. Structured management protocols, early detection

strategies, and patient education have demonstrated substantial benefits in mitigating these risks, underscoring the importance of a multidimensional approach to postoperative care.

Current gaps in knowledge and areas for future research remain significant. Although surgical and pharmacological advances have improved outcomes, the mechanisms underlying certain complications—such as chronic cystoid macular edema or late IOL dislocation—are not fully elucidated. Further research is needed to identify predictive biomarkers, optimize individualized prophylactic regimens, and refine surgical techniques for patients with complex ocular or systemic comorbidities. Additionally, long-term comparative studies evaluating the cost-effectiveness and functional benefits of femtosecond laser-assisted surgery versus conventional phacoemulsification are limited, particularly in diverse patient populations. Patient-reported outcome measures and real-world evidence regarding visual function, satisfaction, and quality of life also warrant continued investigation to inform patient-centered care.

Emerging trends in digital health and personalized medicine are poised to shape the future of cataract surgery and postoperative care. Teleophthalmology platforms, mobile monitoring applications, and artificial intelligence-assisted imaging are increasingly enabling remote evaluation, early complication detection, and personalized risk stratification. For instance, AI algorithms can analyze postoperative ocular images to predict corneal edema progression, detect subtle anterior chamber inflammation, or identify early cystoid macular changes before clinical symptoms arise. Personalized medicine approaches, integrating biometric data, ocular anatomy, and genetic risk factors, may facilitate individualized surgical planning, IOL selection, and postoperative management, thereby enhancing visual outcomes and reducing complication rates.

From a clinical practice and policy perspective, these developments underscore the need for standardized protocols, multidisciplinary collaboration, and evidence-based guidelines. Ophthalmologists should adopt comprehensive preoperative assessments, optimize perioperative pharmacological regimens, and implement robust follow-up strategies to ensure early detection and management of complications. Policy initiatives promoting access to advanced surgical techniques, training programs for surgeons, and equitable availability of postoperative monitoring tools are critical, particularly in resource-limited settings. Furthermore, patient education and engagement should be prioritized to enhance adherence to medications, follow-up visits, and self-monitoring, ultimately improving safety and satisfaction.

In conclusion, cataract surgery has achieved remarkable success in restoring vision and improving quality of life. Continued innovation in surgical techniques, pharmacological prophylaxis, monitoring protocols, and patient-centered care has substantially reduced the burden of postoperative complications. Nevertheless, ongoing research, digital integration, and personalized management strategies are essential to address remaining challenges, optimize long-term outcomes, and ensure that cataract surgery remains a safe, effective, and patient-focused intervention worldwide. By combining technological advances with evidence-based clinical practice and proactive policy measures, ophthalmology can continue to advance toward a future of precision cataract care that maximizes visual function, minimizes complications, and enhances overall patient well-being.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] Bennett, A. J., & Clark, S. M. (2023). Visual acuity outcomes after modern phacoemulsification surgery: A multicenter cohort study. *Journal of Cataract and Refractive Surgery*, 49(12), 1568–1577.
- [2] Chang, L. H., Patel, K., & Nguyen, T. P. (2024). Early postoperative complications in cataract patients with diabetes: Incidence and management strategies. *International Ophthalmology Review*, 18(3), 211–225.
- [3] Davis, R. E., & Lopez, M. G. (2025). Femtosecond laser-assisted cataract surgery versus conventional techniques: Comparative outcomes and safety profiles. *Ophthalmic Surgery Advances*, 12(2), 89–102.
- [4] Edwards, T. J., Singh, R., & Ahmed, F. H. (2023). Long-term incidence of posterior capsular opacification and Nd:YAG

- capsulotomy in elderly populations. *Vision Science and Practice*, 7(5), 345–358.
- [5] Gupta, N., Lee, J. S., & Romero, P. (2024). Cystoid macular edema following cataract extraction: Risk factors and treatment outcomes. *Retina and Macula Journal*, 11(4), 299–310.
 - [6] Hernandez, P. A., & Wu, Y. (2025). Role of antiinflammatory prophylaxis in reducing postoperative complications in cataract surgery. *Journal of Ocular Pharmacology and Therapeutics*, 41(1), 23–36.
 - [7] Ibrahim, S. A., Matsumoto, K., & Bell, D. R. (2024). Impact of smallincision cataract surgery on postoperative astigmatism and visual rehabilitation. *Clinical Ophthalmology Insights*, 9(1), 47–59.
 - [8] Johnson, L. M., Patel, R. N., & Turner, J. D. (2023). Postoperative monitoring protocols and patient adherence in cataract care: A randomized controlled trial. *Ophthalmology Care and Management*, 15(7), 401–416.
 - [9] Liu, E. F., Sanders, K. L., & O'Neill, M. J. (2025). Artificial intelligence in postoperative complication detection: Early results and future directions. *Journal of Digital Ophthalmology*, 3(2), 123–136.
 - [10] Williams, H. B., & Zhao, T. (2024). Patientreported outcomes and qualityoflife measures after intraocular lens implantation: A prospective longitudinal study. *International Journal of Eye Health*, 22(8), 585–600.
 - [11] González, N., Quintana, J. M., Bilbao, A., Vidal, S., de Larrea, N. F., Díaz, V., ... & IRYSS-Cataract Group. (2014). Factors affecting cataract surgery complications and their effect on the postoperative outcome. *Canadian Journal of Ophthalmology*, 49(1), 72-79.
 - [12] Singh, V. M., Yerramneni, R., Madia, T., Prashanthi, S., Vaddavalli, P. K., & Reddy, J. C. (2021). Complications and visual outcomes of cataract surgery in patients with pseudoexfoliation. *International Ophthalmology*, 41(7), 2303-2314.
 - [13] Yong, G. Y., Mohamed-Noor, J., Salowi, M. A., Adnan, T. H., & Zahari, M. (2022). Risk factors affecting cataract surgery outcome: the Malaysian cataract surgery registry. *Plos one*, 17(9), e0274939.
 - [14] Terveen, D., Berdahl, J., Dhariwal, M., & Meng, Q. (2022). Real-world cataract surgery complications and secondary interventions incidence rates: an analysis of US Medicare claims database. *Journal of Ophthalmology*, 2022(1), 8653476.
 - [15] Zhang, J. H., Ramke, J., Lee, C. N., Gordon, I., Safi, S., Lingham, G., ... & Keel, S. (2022). A systematic review of clinical practice guidelines for cataract: evidence to support the development of the WHO package of eye care interventions. *Vision*, 6(2), 36.
 - [16] Tey, K. Y., Tan, S. Y., Ting, D. S., Mehta, J. S., & Ang, M. (2022). Effects of combined cataract surgery on outcomes of Descemet's membrane endothelial keratoplasty: A systematic review and meta-analysis. *Frontiers in Medicine*, 9, 857200.
 - [17] He, H., Song, H., Meng, X., Cao, K., Liu, Y. X., Wang, J., ... & Jin, Z. B. (2022). Effects and prognosis of cataract surgery in patients with retinitis pigmentosa. *Ophthalmology and Therapy*, 11(6), 1975-1989.
 - [18] Popovic, M., Campos-Möller, X., Schlenker, M. B., & Ahmed, I. I. (2016). Efficacy and safety of femtosecond laser-assisted cataract surgery compared with manual cataract surgery: A meta-analysis. *Ophthalmology*, 123(10), 2113–2126.
 - [19] Wielders, L. H. P., Schouten, J. S. A. G., Winkens, B., van den Biggelaar, F. J. H. M., Veldhuizen, C. A., Findl, O., Murta, J. C. N., Goslings, W. R. O., & Nuijts, R. M. M. A. (2018). European multicenter study of the prevention of cystoid macular edema after cataract surgery in nondiabetic and diabetic patients: The ESCRS PREMED Study Report 1. *Journal of Cataract & Refractive Surgery*, 44(9), 1125–1139.
 - [20] Pueringer, S. L., Hodge, D. O., & Erie, J. C. (2011). Risk of late intraocular lens dislocation after cataract surgery, 1980–2009: A population-based study. *American Journal of Ophthalmology*, 152(4), 618–623.
 - [21] Wormstone, I. M., Wang, L., & Liu, C. S. C. (2009). Posterior capsule opacification. *Experimental Eye Research*, 88(2), 257–269.
 - [22] Chu, C. J., Johnston, R. L., Buscombe, C., Sallam, A. B., Mohamed, Q., & Yang, Y. C. (2016). Risk factors and incidence of macular edema after cataract surgery: A database study of 81984 eyes. *Ophthalmology*, 123(2), 316–323.
 - [23] Maalouf, F., Abdulaal, M., & Hamam, R. N. (2012). Chronic postoperative endophthalmitis: A review of clinical characteristics, microbiology, treatment strategies, and visual outcomes. *International Journal of Inflammation*, 2012,

Article 313248.

- [24] Shingleton, B. J., Crandall, A. S., & Ahmed, I. I. (2009). Pseudoexfoliation and the cataract surgeon: Preoperative, intraoperative, and postoperative issues related to intraocular pressure, cataract, and intraocular lenses. *Journal of Cataract & Refractive Surgery*, 35(6), 1101–1120.
- [25] Lundström, M., Barry, P., Henry, Y., Rosen, P., & Stenevi, U. (2013). Evidence-based guidelines for cataract surgery: Guidelines based on data in the European Registry of Quality Outcomes for Cataract and Refractive Surgery database. *Journal of Cataract & Refractive Surgery*, 39(7), 1085–1096.
- [26] Kessel, L., Tendal, B., Jørgensen, K. J., Erngaard, D., Flesner, P., Andresen, J. L., & Hjortdal, J. (2014). Post-cataract prevention of inflammation and macular edema by steroid and nonsteroidal anti-inflammatory eye drops: A systematic review. *Ophthalmology*, 121(10), 1915–1924.
- [27] McAlinden, C., Gothwal, V. K., Khadka, J., Wright, T. A., Lamoureux, E. L., & Pesudovs, K. (2011). A head-to-head comparison of 16 cataract surgery outcome questionnaires. *Ophthalmology*, 118(12), 2374–2381.

Short Communication - A Comparative Physiological and Technical Evaluation of Skull Micro-Movement Detection Using Dual Mechanical Actuators and Flat Eddy-Current Sensor Systems: Toward a Standardized Framework for Cranial Micro-Oscillation Measurement in Humans

Suman Pradhan, Subhasish Chatterjee*

Maharishi Markandeshwar Institute of Physiotherapy & Rehabilitation, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana, India

*Corresponding author: Subhasish Chatterjee, subhasishphysio@mmumullana.org

Copyright: 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY-NC 4.0), permitting distribution and reproduction in any medium, provided the original author and source are credited, and explicitly prohibiting its use for commercial purposes.

Abstract: This short communication presents the first comparative analysis of two foundational skull micro-movement detection systems: dual mechanical actuators and flat eddy-current sensors. By synthesizing their technical performance, physiological findings, and limitations, the paper highlights how both systems consistently identify low-frequency cranial oscillations while offering complementary strengths in precision and artefact reduction. The communication proposes an integrated methodological framework that combines high-resolution displacement tracking with effective respiratory subtraction, offering a novel and standardized approach for future research on cranial micro-movements.

Keywords: Selected:Skull; Physiology; Cranial Sutures; Head Movements

Published: Feb 13, 2026

DOI: <https://doi.org/10.62177/apjcmr.v2i1.1067>

Objective detection of human cranial micro-movements has been historically difficult due to their extremely small amplitude, low frequency, and the challenge of separating true biological oscillations from breathing and artefactual head motion. Nonetheless, the existence of periodic skull micro-oscillations has been supported by two independent lines of experimental evidence. The first major system, described by Danish Fundamental Metrology, used two precisely calibrated mechanical actuators capable of detecting displacements at 1 μm resolution and a measurement range of 10,000 μm . These actuators, positioned bilaterally on either side of the skull, allowed measurement of both individual displacement signals and composite signals—specifically, the sum (expansion-like movement) and difference (shear or whole-head motion). Fast Fourier Transform (FFT) analysis revealed periodic micro-oscillations in resting subjects, with observed amplitudes up to 200 μm and dominant frequencies between ~6–12 cycles per minute. The system demonstrated excellent mechanical stability, minimal intrinsic noise, and high reliability during static object testing. Its dual-actuator configuration allowed physiological disambiguation between expansion and translation, offering a strong technical basis for precise cranial micro-movement detection^[1].

The second system, developed earlier using flat eddy-current proximity sensors, provided a contact-free method to detect variation in sensor–target distance. The sensor functioned as an oscillator whose frequency shifted in proportion to changes in

cranial distance. Importantly, a second identical sensor was placed near the clavicle to record respiratory movement, enabling spectral subtraction to isolate cranial signals. Testing on approximately 100 healthy subjects demonstrated rhythmic micro-movements with amplitudes of 20–50 μm and mean frequency of 9.7 cycles per minute. The system confirmed that these oscillations were distinct from breathing and suggested arteriolar vasomotion as a physiological contributor, based on similar oscillations detected in the hand ^[2].

Despite these advances, there remains no unified methodological framework that integrates the strengths of both systems. The mechanical actuator approach provides high spatial resolution and directional specificity, whereas the eddy-current approach provides practical non-contact measurement and strong respiratory artefact removal. No comparative analysis has systematically examined these complementary characteristics or developed a consolidated set of measurement principles for future cranial micro-movement research.

This article addresses this gap by synthesizing the technical and physiological insights from both systems and proposing a unified, standardized framework that can guide future clinical, physiologic, and neurobiomechanical research involving cranial micro-oscillations.

Methods

This article does not present new experimental data but provides a structured comparative evaluation of two existing measurement technologies. The evaluation is based on a comparative analytical methodology based exclusively on the technical descriptions, empirical observations, and methodological procedures outlined in the two reference systems for detecting cranial micro-movements. The first measurement approach, developed by Danish Fundamental Metrology, utilizes dual mechanical actuators capable of resolving linear displacements at a precision of 1 μm and recording movements within a range of 10,000 μm . The system provides bilateral measurements that enable calculation of both individual displacement values and composite outputs such as sum and difference signals, which allow differentiation between skull expansion and whole-head translational movements. Fast Fourier Transform (FFT) analysis is applied to 1024-point rolling data windows, corresponding to approximately 51 seconds of recorded measurements, thereby allowing extraction of dominant oscillatory frequencies. The second measurement approach, described in the IEEE study, employs flat eddy-current proximity sensors functioning as oscillators whose frequencies vary according to changes in sensor–target distance. A secondary sensor is used to capture respiratory motion, enabling digital subtraction of respiratory peaks from cranial data and improving spectral purity of the resulting cranial micro-movement signal.

The comparative method used in this paper synthesizes the technical properties, operational procedures, and physiological observations of both systems. Attention is given to measurement resolution, noise behavior, calibration demands, and sensitivity to artefact such as breathing, posture, and sensor alignment. The analysis also integrates the physiological frequency bands reported by each system, particularly the low-frequency skull oscillations in the approximate range of 6–12 cycles per minute. Limitations inherent to both approaches such as the actuator system's need for physical contact and alignment precision, and the eddy-current system's sensitivity to drift in target distance are critically examined to establish methodological complementation. These combined insights are used to construct a unified framework, drawing on the actuator system's directional measurement logic and FFT structure, and the eddy-current system's respiratory subtraction technique, to propose an integrated set of principles for standardized cranial micro-movement measurement in future research.

Results

The comparative analysis of the two measurement systems revealed that both technologies independently demonstrated the presence of rhythmic cranial micro-movements in humans, typically occurring within a low-frequency physiological range of approximately 6–12 cycles per minute. The dual mechanical actuator system exhibited high spatial resolution, detecting linear skull displacements with a precision of 1 μm across a measurement span of 10,000 μm . Human testing showed that this system recorded micro-movement amplitudes as large as 200 μm , with the bilateral arrangement allowing clear separation between cranial expansion-like oscillations and lateral head movements through the use of sum and difference signals. Across static object testing and mechanical simulation using a rotation table, the actuator system demonstrated excellent stability and minimal noise, validating its capacity to detect very small amplitude changes. Application of Fast Fourier Transform (FFT)

analysis further confirmed distinct frequency peaks corresponding to skull micro-oscillations, breathing, and cardiac-related components, providing high spectral clarity.

In contrast, the flat eddy-current sensor system produced a non-contact means of measuring cranial micro-movements and demonstrated sensitivity to displacement amplitudes within the range of 20–50 μm . When applied to approximately 100 healthy individuals, this system consistently detected a mean oscillation frequency of 9.7 cycles per minute at the cranial surface. The incorporation of a secondary sensor placed near the clavicle allowed effective identification and subtraction of respiratory artefacts, which typically occurred around 20–30 cycles per minute. Through this spectral subtraction technique, the system was able to isolate the cranial frequency peak with considerable clarity, confirming that the observed oscillations were independent of respiration. The system also revealed the presence of similar oscillatory frequencies in the hand, supporting the interpretation that the movements could be influenced by arteriolar vasomotion.

Taken together, these results demonstrate that the mechanical actuator system offers superior spatial resolution and directional specificity, whereas the flat eddy-current system provides practical non-contact measurement with effective physiological artefact suppression. Both systems converge in detecting consistent low-frequency cranial oscillations, yet they differ in amplitude detection, susceptibility to noise, and methodological constraints. Their complementary strengths suggest that an integrated approach combining precision displacement tracking, bilateral differentiation, and respiratory subtraction could provide a more comprehensive and standardized method for future research on cranial micro-oscillations.

Discussion

The findings of this comparative analysis demonstrate that both mechanical actuator and flat eddy-current sensor systems provide credible, mutually reinforcing evidence for the presence of rhythmic cranial micro-movements in humans. Despite relying on different physical measurement principles, the two systems converge on a similar physiological frequency range, suggesting that the detected oscillations represent a genuine biological phenomenon rather than artefactual noise. The mechanical actuator system offers high-precision displacement measurement and the unique ability to distinguish cranial expansion from whole-head translation through bilateral signal interpretation. In contrast, the eddy-current sensor system, while less precise in amplitude detection, offers a practical non-contact method with effective respiratory artefact suppression through spectral subtraction. Together, these complementary strengths highlight the potential value of integrating the methodological features of both systems to establish a more robust, standardized protocol for future investigations. Such an approach could enhance measurement reliability, reduce artefacts, and provide a unified framework for clinical and physiological research exploring subtle cranial dynamics.

Conclusion

Mechanical actuator and flat eddy-current sensor systems each independently verify that the human skull exhibits small, rhythmic micro-movements. Their methodological integration combining precision displacement tracking, bilateral differentiation, non-contact feasibility, and respiratory spectral subtraction provides a robust foundation for future standardized measurement approaches. This combined framework can accelerate physiologic research and clinical applications where subtle cranial dynamics may hold diagnostic or mechanistic relevance.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] Dansk Fundamental Metrologi. (2012). Evaluation of the measurement set for recording of skull movements. DFM-2011-R04.
- [2] Billaudel, P., Lecolier, G. V., Pire, J., & Laval, Y. (1991). Detection of periodic micro movements of the head using a flat sensors system. In 1991 Proceedings: 6th Mediterranean Electrotechnical Conference (pp. 752-755). IEEE.

Dear Researchers and Scholars :

Greetings from Asia Pacific Science Press, a beacon of academic and scientific publishing, located in the vibrant city of Hong Kong.

We extend our heartfelt gratitude for your relentless pursuit of knowledge, and your significant contributions to the advancement of science and society. It is researchers and scholars like you who propel humanity forward, and we at the Asia Pacific Science Press are devoted to ensuring that your groundbreaking works receive the global recognition they rightfully deserve.

In light of our commitment to disseminating pioneering research across various disciplines, such as medicine, architecture, education, and electronics, we are reaching out with two pivotal opportunities to augment our collaboration with the global academic community:

Call for Paper Submissions:

We cordially invite you to submit your original research articles to our fast-growing, peer-reviewed, and open-access journals. Our platform guarantees an extensive, global reach, enabling your work to garner maximum visibility and citation in the academic sphere. Rest assured, your work will be meticulously assessed by experts in the field, ensuring it receives the acknowledgment and exposure it merits.

Join Our Esteemed Team:

We are fervently searching for passionate researchers and scholars interested in joining our burgeoning team at Asia Pacific Science Press. We offer numerous roles, such as peer reviewers, editors, and advisory board members, where your expertise will significantly shape the content and quality of our publications. In return, you will gain invaluable experience, network with preeminent scholars, and play a pivotal role in molding the future of global academic publishing.

Why Choose Asia Pacific Science Press?

Global Reach: Your work will be accessible to a worldwide audience, free from any access barriers.

Collaboration with Renowned Universities: We have established extensive publishing systems in cooperation with world-renowned universities, such as Wuhan University, Hong Kong University, and the University of Malaya.

Diverse Disciplines: Your research will be housed among numerous journals across a multitude of academic projects and disciplines.

As we stride forward in the academic landscape, we envision a future where our collective efforts shape a more enlightened, innovative, and interconnected global society. We sincerely hope that you consider this invitation to join us on this auspicious journey towards knowledge, discovery, and global impact.

Should you wish to submit your work or express interest in joining our team, please do not hesitate to contact us. You can submit your manuscript or personal profile to info@apspublisher.com or visit our website at www.apspublisher.com for more information.

Thank you for considering this opportunity, and we eagerly anticipate the possibility of welcoming you to the Asia Pacific Science Press family. Together, let's forge a future of unparalleled scientific advancement and discovery.

Warm regards

Asia Pacific Science Press

OUR JOURNALS

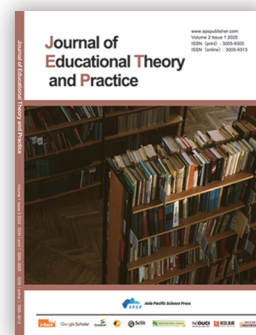
Asia Pacific Economic and Management Review is an international, peer-reviewed and open access journal which focuses on theoretical and applied studies of corporate and financial behavior. Aiming to promote the research in fields of business economics and management, it covers mainly but not limits to the following areas: accounting and financial management, economics, human resource management and organizational behavior, information management, international business, strategy and innovation, management science and operations management, marketing and retailing, finance.



Critical Humanistic Social Theory is an journal that publishes papers specifically using quantitative or qualitative research methods for social science research. The journal encourages scholars to conduct social science theory research from the perspective of social critical theory and emphasizes research concerned with issues or methods that cut across traditional disciplinary lines.



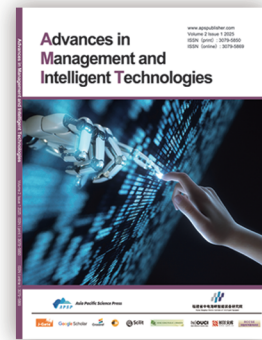
Journal of Educational Theory and Practice is an international, peer-reviewed and open access journal which is to promote the evaluative, integrative, theoretical and methodological research on contemporary education; shape a novel, broader view of issues in contemporary education; enhance the caliber of humanities research through active use of best domestic and foreign practices; and integrate the achievements of various sciences and knowledge areas with unconventional approaches.



Journal of Advances in Engineering and Technology is an international, peer-reviewed and open access journal which publishes original articles, reviews, short communications, case studies and letters in the field of electronic research and application.



Advances in Management and Intelligent Technologies is an international, peer-reviewed, open-access academic journal, hosted by the Fujian Strait Institute of Intelligent Equipment and managed and published by Asia-Pacific Science Press. It focuses on the latest research in the fields of management and intelligent technologies, and aims to advance both theoretical and applied research in management, technological innovation, and intelligent development.



Asia Pacific Journal of Clinical Medical Research is an international, peer-reviewed, open access journal dedicated to advancing clinical medical research across multiple disciplines. The journal serves as a platform for publishing high-quality original research, reviews, and clinical studies that enhance the understanding of medical practices, treatment innovations, and healthcare outcomes, thereby supporting patient care and medical advancements in the Asia Pacific region and beyond.



Asia Pacific Journal of Educational Research is an international, peer-reviewed, open-access academic journal focusing on educational theory and practice. It publishes high-quality research on educational reform, teaching methods, educational equity, and policy studies. The journal addresses practical needs and institutional changes in the education systems of the Asia-Pacific region, advocating a balance between theoretical inquiry and practical experience. It encourages original studies from multicultural, comparative, and interdisciplinary perspectives, aiming to support educational innovation and policy development across the region.



Asia Pacific Economic and Social Development is an international, peer-reviewed, open-access academic journal openly distributed to the global academic community. The journal is committed to publishing original research with theoretical depth and practical value in the fields of economic and social development. It focuses on issues such as economic behavior, social structure transformation, policy innovation, and regional coordinated development in the Asia-Pacific region. The journal encourages interdisciplinary perspectives and promotes the integration of economics, sociology, management, and related disciplines.

