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Reviews

Smart Contact Lenses: Ocular Biosensing, Medicolegal Implications, and Technological Challenges

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SUMMARY

Background: Smart contact lenses (SCL) are embedded with biosensors, microchips, antennae, and micro channels to enable technologically advanced functioning beyond that of regular lenses. Common materials include graphene, polyethylene terephthalate, and polymethyl methacrylate, with power supplied by RFID and NFC technologies. These lenses enable wireless data transmission to smartphones and smartwatches for real-time health management and monitoring, including non-invasive tear glucose assessment, ocular drug delivery, and monitoring of cortisol, cholesterol levels, pH, temperature, and electrolytes.

Aim: This review evaluated the technological advancements, healthcare applications, and medicolegal challenges of SCL's to assess their potential for safe clinical and medicolegal implementation.

Methodology: A comprehensive literature search was conducted in PubMed, Google Scholar and Web of Science for articles published between 2005 and 2025, focusing on SCL design, biosensing capabilities, clinical risks, and medicolegal implications.

Result: Smart contact lenses demonstrate promising application in non-invasive monitoring and targeted therapy. However, widespread adoption is limited by several challenges, including improper handling, prolonged use and poor hygiene, leading to ocular complications. Additionally, wireless data transmission poses privacy and cybersecurity concerns, as it increases the risk of unauthorized data access.

Conclusion: Adherence to the principle of informed consent and provider transparency is crucial to ensure safe and responsible utilization of SCLs in both clinical and legal contexts. Addressing biocompatibility and data security will facilitate widespread adoption.

Keywords: Biomedical Engineering, Cybercrime, Cybersecurity, Medicolegal, Smart Contact Lenses.

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INTRODUCTION

Smart contact lenses (SCLs) are advanced lenses equipped with microelectronics, sensors and antennae, enabling them to track a wide array of physiological functions using the eye's movement, as well as performing the function of visual correction [1–4].

There are numerous common conditions for which the diagnostic and monitoring procedures are invasive, time consuming, and restricted to the hospital setting, with results typically provided during hospital visits; this affects both diagnosis and continuous monitoring of such conditions. Furthermore, advancements in living standards and quality of life have increased the demand for personalized healthcare. Smart contact lenses are a self-monitoring device allowing physiological and biochemical changes to be monitored continuously and non-invasively, through tears. They can aid diabetes diagnosis and glucose monitoring, as well as detect changes in intraocular pressure, electrolyte balance, cholesterol level, cortisol level, temperature, and pH, among others [1–5]. They also find application in ocular drug delivery for various diseases. For these reasons, SCLs are drawing significant attention, among various wearable healthcare devices, for their potential utility in health management.

Moreover, SCLs present potential forensic implications, mainly through their biosensing and wireless data transmission capabilities. Current prototypes are designed primarily for physiological monitoring, including parameters such as glucose levels, intraocular pressure, cortisol, and temperature. More advanced features, such as integrated micro-cameras, biometric identification, and GPS tracking, are still under experimental development and not yet integrated into standard SCL technology.

METHODOLOGY

Study design: This is a narrative literature review on the applications, medicolegal implications, and technological challenges associated with smart contact lenses (SCL).

Search strategy: A comprehensive literature search was conducted in PubMed, Google Scholar, and Web of Science for articles published between 2005 and 2025. Search terms were combined using Boolean operators and included "smart contact lens" OR "wireless contact lenses" AND "bio sensing" OR "glucose" OR "cortisol" OR "intraocular pressure" OR "diabetes" OR "theranostic" OR "drug delivery". To include preclinical developments, no animal or human clinical trial restrictions were applied. More than 100 studies were identified through the database search. After removal of duplicates, 53 articles were screened based on title and abstract; 30 articles were excluded, leaving a total of 23 studies included in the review.

Eligibility criteria: Studies were included if they demonstrated the application of SCLs with wireless sensing (glucose, cortisol, intraocular pressure, integrated theranostics, or broader uses such as camera, GPS, biometrics, or video recording), and were written in the English language.

Articles not pertaining to SCLs or not written in English were excluded.

RESULTS

The emerging smart contact-lens platform integrates biosensing, therapeutic drug delivery, wireless data transmission, microfluidic systems, and forensic applications. As shown in Table 1, these technologies offer non-invasive and continuous physiological monitoring, while also presenting technical, ethical, safety, security, and cost-related challenges.

Evolution of smart contact lenses

The first smart contact lens, developed by Leonardi et al. and introduced in 2003, was a prototype designed primarily as a biosensing platform rather than a multifunctional digital device. The prototype incorporated miniaturized sensing components embedded within a soft contact lens to enable physiological monitoring through tear fluid. This represented the first step toward wearable

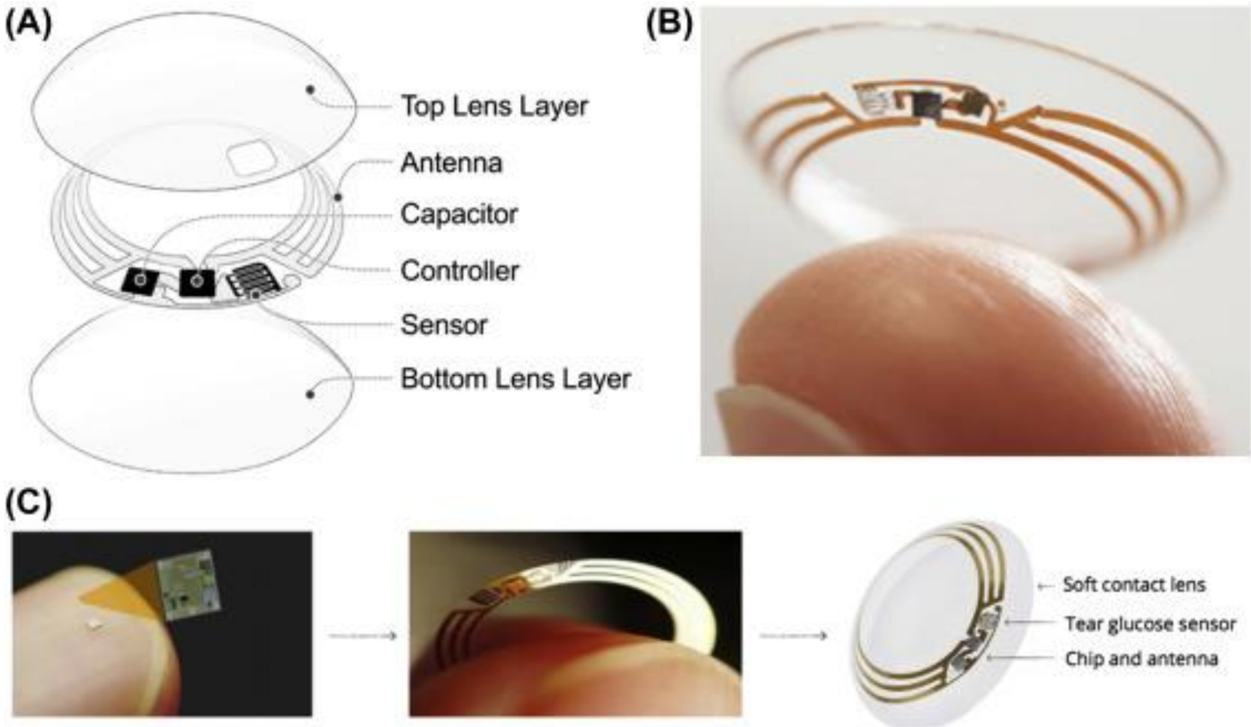

Figure 1. Diagrammatic representation of recently launched smart contact lens. (A) Schematic diagram (B) Sensor prototype (C) Wireless chip mounted with sensor on an electronic ring and then embedded into the contact lens.

ocular biosensors and demonstrated that electronic components could be safely integrated into contact lens materials. Over time, advancements in the micro-fabrication industry led to the development of more advanced lenses. For example, the first SCL to monitor intraocular pressure was developed in 2008; a SCL for glucose monitoring was developed in 2011, although that particular project was discontinued in 2017 due to inaccuracies in blood glucose measurement using tears; in 2019, a SCL was developed for the treatment of dry eyes; and gaze tracking was introduced in 2020 [6]. In 2024, Park et al. developed a SCL glucose biosensor that could transmit data wirelessly to the user's phone [7]. Long-term reliability data are sparse, with uncertainties related to sensor degradation, biofouling, and tear film variability over extended wear. These limitations have significant medicolegal implications, as clinical decisions based on insufficiently validated or poorly concordant data may expose clinicians and manufacturers to liability. Further research is required, focusing on standardized validation protocols, large-scale comparative studies, and longitudinal performance assessment to ensure that SCL outputs are both clinically reliable and legally defensible.

Design and mechanism of a smart contact lens

A SCL designed for non-invasive biosensing is composed of multiple integrated micro-components within a soft lens matrix (Figure 1). The lens includes a biochemical sensor that comes into contact with tear fluid to detect analytes such as glucose; a microcontroller (chip) that processes the sensed signal; and an antenna that enables wireless transmission of data to an external device. Supporting elements like a capacitor help to store or manage power, often supplied wirelessly, while the structure is enclosed between top and bottom lens layers that ensure transparency, protection of electronics, and biocompatibility with the ocular surface. Overall, the system works by detecting changes in tear composition, converting them into electrical signals, processing them within the embedded circuitry, and transmitting the information wirelessly for real-time monitoring [8].

Smart contact lens materials include conductive materials such as graphene, gallium-indium alloy, and silver nanowires, combined with hydrogels such as polydimethylsiloxane (PDMS), silicone, poly 2-hydroxyethyl methacrylate (PHEMA), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), and 2-methacryloyloxyethyl phosphorylcholine (MPC) [7].

Smart contact lenses (SCLs) require an integrated power source to operate electronic components such as sensors and displays. Several powering strategies have been investigated, and these should be considered as alternative, rather than universally coexisting, approaches. In RF-powered SCLs, radio-frequency energy is received by an antenna and converted into direct current by a rectifier. The harvested energy can then be regulated by a power-management circuit and stored in a capacitor to provide a stable power supply to the integrated electronics [7,9]. An alternative approach is biochemical energy harvesting, in which electroactive substances present in tear fluid, such as glucose or ascorbic acid, participate in electrochemical reactions at anode and cathode electrodes to generate electrical energy that can power the lens [7–9].

Display technologies represent a separate functional component of the SCL. Ma et al. demonstrated a microscale LED fabricated with graphene and integrated onto a soft contact lens. The prewired device, operated at approximately 9 V, demonstrated electrical continuity and mechanical robustness. Graphene also provided electromagnetic-interference shielding and maintained the flexibility required for contact lens integration [9,10]. In a separate wireless-display architecture, an antenna, rectifier, and LED pixel were integrated into the lens so that externally supplied RF energy could be converted into electrical power for the display [11]. Conductive materials such as silver microwires, silver nanowires, or carbon-based conductors may be used as interconnects to electrically connect the different components of an SCL, depending on the specific device architecture [7,9].

The principle of microfluidics applies in smart contact lenses, relying on capillary force, fluid surface tension, fluidic resistance, and energy dissipation. Tears are collected naturally, when the eye blinks. Capillary force ensures that tear fluid on the SCL's surface enters its micro-channels. Here, the Reynolds number becomes a significant parameter in determining the resistance in the flow of fluid. The laminar flow of ocular fluid through the micro-sensor-lined micro-channels aids accurate measurement of ion concentration, pH, and other biomarkers [9,10].

Smart contact lenses can transmit and receive data to and from external devices, such as smartphones or medical monitoring devices, thereby facilitating real-time tracking of health and rapid therapeutic responses, which is important in chronic diseases like diabetes and glaucoma. Antennae play an important role in transmitting the information from the lens, and should be carefully designed to preventing obstruction of vision [9].

Application of smart contact lenses

Diabetes

Rapid screening and diagnosis of disease have become significant aspects of preventive medicine, improving treatment strategies and reducing further complications. As such, they will also reduce the future burden on healthcare systems [11,12]. In this context, smart contact lenses have attracted significant attention as a new model for diabetes management through continuous monitoring of tear fluid [13,14]. While frequent blood glucose monitoring using conventional methods is an invasive process, causing pain and discomfort to the patient [14,15], tears have emerged as a promising alternative to blood for both diagnosis and monitoring of diabetes [15]. There are five main components of a glucose-monitoring SCL: an on demand drug delivery system (f-DDS), a real-time electrical biosensor, a complementary integrated circuit-based micro controlled chip with a power management unit, a resonant inductive wireless energy transfer system, and a remote RF communication system. Glucose is detected in the tear fluid by the real-time biosensor; the flexible drug delivery system can then release the drug via remote communication. The resonant inductive power transfer permits wireless transfer from an external power source with a transmitter coil, allowing the device to communicate with the external controller via the RF communication system [3]. Smart contact lenses finds application both in continuous glucose monitoring through tears and in the treatment of diabetic retinopathy [3,16].

Drug delivery and therapy

Various strategies exist for drug delivery in ocular diseases, including eye drops and injections. Intraocular injections, while used to treat various conditions, are invasive and uncomfortable; nowadays, eye drops are the most commonly used method of ocular drug delivery. However, washout of the drops, side effects, and poor patient compliance remain some of the drawbacks of this method. SCLs minimize drug washout caused by blinking, thereby increasing the drug's bioavailability and therapeutic effects [17,18]. Thus, SCLs have become an attractive option, given their non-invasive nature, on-demand drug delivery, and the high bioavailability of drugs administered via this route [17]. Due to recent advances in SCL materials, improved patient compliance with this method, and the sustained drug delivery it allows, SCLs are used for long-term treatment of eye diseases like glaucoma and diabetic retinopathy [3,19].

Cortisol monitoring

Cortisol is a glucocorticoid hormone produced by the adrenal glands. This production is governed by the suprachiasmatic nucleus, which monitors the body's circadian rhythm and regulates the hypothalamic-pituitary-adrenal axis [20]. Hypothalamic corticotropin-releasing hormone stimulates the pituitary gland to secrete adrenocorticotropin hormone, which in turn stimulates the adrenal glands to secrete cortisol. This system is known as the hypothalamic-pituitary-adrenal axis. Chronic stress causes abnormal secretion and accumulation of cortisol [21,22]. Excess cortisol increases risk of obesity, diabetes, cardiovascular disease, respiratory failure, infection, depression, and anxiety disorder, while low cortisol levels lead to Addison's disease, weight loss, and chronic fatigue [10,21]. Conventional cortisol monitoring methods, such as immunoassay and chromatography, require bulky equipment that limits its use in mobile healthcare systems. More recently, sensors have been developed, incorporating graphene field effect transistors, to detect low cortisol levels, with a detection limit of 10pg/ml (low enough to detect cortisol in tears) [11,22]. SCLs equipped with cortisol sensors are integrated with wireless communication circuits and transparent antennae, operable by a mobile phone without obstructing the wearer's view [11,22].

Medicolegal significance of smart contact lenses

Determination of cause of death

As SCLs can monitor overall body activity, they offer significant utility in determining cause of death. They can be used to ascertain the manner of death: suicide, homicide, or accidental. If the wearer has a glucose monitoring lens and dies due to hyperglycemia or hypoglycemia, the lens can provide a timeline of the hyper- or hypoglycemic state. If a wearer dies from a neurological disorder (anxiety, depression) or cardiovascular disease (stroke, heart failure), SCLs can help to determine their health status at the time of death, and rule out suicide and homicide. SCL microsensors, as well as detecting changes in the body's physiological activity, can also detect the presence of toxic compounds in the event of poisoning. They can track body temperature, heart rate, intraocular pressure, and pH changes, all useful signs in a poisoning case. SCLs can also incorporate micro-cameras, which can record the surroundings and people present with the wearer before their death, or the wearer's final actions before becoming unconscious. This feature is largely still in the experimental stage, but is not far from reality. In cases of homicide, the camera can record the suspect's face, blink rate abnormalities, environment of the crime scene, conversation audio, fear response or struggle, which can be important to the investigation.

Determination of time of death

Smart contact lenses can detect tear composition, last blinking movement, ocular changes, and last signal before system shutdown, as well as record the last physiological activities, such as a drop in intraocular pressure, glucose in tears, decreased oxygenation, and body temperature changes. All of these can help in determining the time of death. They can also detect the post-mortem rise in potassium level, similar to the conventional autopsy method of measuring potassium in the vitreous humour—one of the most reliable indicators of time since death.

Evidence of assault or struggle

In case of assault, the victim will experience a rapid rise in cortisol, dilatation of the pupils due to fear, and increased intraocular pressure. SCLs can detect these changes and identify the state of acute stress. In addition, any damage to the lenses, such as scratches, breaks or tears, or displacement of the lens from its position, might indicate physical violence. If the lens is embedded with a camera, it can also record the face of the attacker; this can be presented as evidence in a court of law, thereby aiding the course of justice.

Evidence in court cases

Smart contact lenses can be submitted as evidence in a court of law and can strongly impact the court's final ruling. The victim's environment before their death, their physiological activity and mental status, conversations prior to death, and any violence, blackmail or threats, can all be presented before the court.

In terms of medical negligence, if a patient's death is caused by the failure of a SCL to monitor glucose levels adequately, or to deliver medication for diabetes, glaucoma, or any disease suffered by the patient, this may be deemed medical negligence on the part of the treating doctor or the SCL manufacturer.

Digital forensics

Smart contact lenses with embedded microchips can continuously capture, process, and store physiological and usage data, making them a potentially valuable source of digital evidence in forensic investigations. These devices can log parameters such as biometric readings (e.g., glucose levels, intraocular pressure), timestamps, duration of wear, and wireless transmission records, which may aid timeline reconstruction in cases involving medical events, negligence, or unexplained deaths. Because the data are generated in real time and in close association with the wearer, they can provide objective, time-stamped physiological insights that are difficult to obtain through traditional methods. However, for such data to be admissible in legal proceedings, they must meet standards of authenticity, integrity, and chain of custody, as required under frameworks like the Indian Evidence Act. Challenges include ensuring data security against tampering, validating device accuracy, and interpreting algorithm-processed outputs, especially when proprietary systems are involved. Additionally, issues of data ownership, consent, and privacy must be addressed before forensic use, as unauthorized access or misuse could violate legal protections. Thus, while SCLs hold promise for forensic applications, their evidentiary value depends on robust technical validation, secure data handling, and clear legal governance.

Data breach in smart contact lenses

Because SCLs have the capacity to gather and store myriad personal and intimate user details, concerns have been raised regarding privacy, data security, and intellectual property. While they offer many advantages in the context of health care, the constantly-collected information, some of which may be beyond the user's knowledge, could be used against them by cybercriminals and marketers [22].

Another cybersecurity threat arises due to the reliance of SCLs on wireless data transmission. Such risk in SCLs is not merely an extension of generic Internet of Things (IoT) threats, but arises from their unique ocular interface, continuous biosensing, and short-range wireless architecture. Unlike conventional wearables, these devices operate in direct contact with the cornea and rely on near-field communication and wireless power transfer, making them susceptible to proximal attacks such as skimming, eavesdropping, and relay interference that may occur without user awareness. More critically, the integrity of biosensor data (e.g., tear glucose or intraocular pressure) can be affected not only by physiological variability but also by firmware tampering or signal manipulation, potentially causing clinically misleading outputs and downstream harm. From a medicolegal perspective, this raises concerns regarding the reliability, authenticity, and auditability of data, all of which are essential for admissibility under frameworks such as the Indian Evidence Act. SCLs open a new door for cybercriminals to access data. It is possible that the suicide rate might even increase due to misuse of this new technology [22].

Mojo Vision's smart contact lens was once just a concept. As it moves from idea to commercial reality, existing laws, which do not address such advanced technology, will undoubtedly evolve. By addressing privacy concerns and data security measures, protecting intellectual property rights, and ensuring compliance with healthcare regulations, the potential of this technology can be harnessed while ensuring user safety. Nonetheless, SCLs are likely to face numerous future obstacles due to their potential for abuse [22].

Challenges and limitations of smart contact lenses

Smart contact lenses are embedded with biosensors and microchips, making them expensive to purchase. Prices are expected to vary from 1000 USD to 2000 USD, with the basic model of intraocular pressure detecting lens starting at 650 USD [23].

Furthermore, the materials used in SCLs can irritate the eyes or cause side effects with prolonged use. Improper handling and maintenance also represent major challenges, with some studies indicating patient non-compliance due to difficulties or inconvenience in this regard. Poor hygiene and careless handling may increase the risk of infection. Moreover, patients may not wear their prescribed lenses consistently due to the cost or discomfort of certain lenses, causing potential complications [23]. Patients are typically compliant in cases of short-term use, but become non-compliant with longer-term use, which can cause eye dryness, allergy, corneal injury, and some chronic side effects [24].

Some crucial challenges exist regarding the design of SCLs. The constituent material of micro-channels, which guide the flow of fluid, can sometimes swell, changing the path and speed of the fluid and affecting the accuracy of the lens [7,22]. Improper placement of antennae, biosensors or microchips can block the wearer's vision. Collection of tear fluid over the lens causes scattering of light, which makes the wearer's vision hazy.

Because SCLs have sensors and micro-cameras that can connect wirelessly to other devices, they are susceptible to hacking. This raises privacy concerns not only for the wearer, but also the people around them. Hacking carries a high chance of misuse of personal and sensitive information; in the case of SCLs it can be used for unauthorized surveillance of homes, offices, hotels, etc., without the occupants' knowledge, presenting a serious security threat.

Privacy and data protection concerns

There is a serious privacy concern inherent in any device that captures personal data for wireless transfer. For the wearer's security, providers must ensure that all transmitted data is encrypted to prevent unauthorized excess. Traditional one-time consent models are insufficient for continuously-operating, datagenerating devices; instead, dynamic or ongoing consent frameworks are more appropriate, allowing users to control how their data are collected, processed, and shared over time. This aligns with modern data protection principles emphasized in regulations such as the General Data Protection Regulation (GDPR), which stress transparency, purpose limitation, and user autonomy [25].

Data ownership also remains a contested issue. While users generate physiological data, device manufacturers and platform providers often control storage and analytics, creating ambiguity over who owns and can commercialize the data. Regulatory frameworks such as the Health Insurance Portability and Accountability Act (HIPAA) recognize patient rights over health information, yet gaps persist when devices operate outside traditional healthcare systems [26]. Clear contractual agreements and regulatory oversight are therefore essential to define ownership, access rights, and secondary use.

Liability is another critical concern, particularly in cases of device malfunction, inaccurate readings, or data breaches. Manufacturers may be held accountable under product liability principles, while healthcare providers could face negligence claims for clinical decisions reliant on inaccurate sensor data. Foundational case law such as Donoghue v Stevenson establishes the duty of care owed by manufacturers to end users, which is increasingly relevant to digital medical devices [27].

Finally, the evidentiary admissibility of SCL-generated data is an emerging legal issue. For such data to be accepted in courts, it must meet standards of reliability, authenticity, and chain of custody, as outlined in legal frameworks such as the Indian Evidence Act [28]. Concerns regarding data integrity, potential tampering, and algorithmic opacity may challenge admissibility unless robust validation and audit mechanisms are in place. Industry perspectives, including developments reported by Mojo Vision, further highlight the evolving legal landscape surrounding SCL technologies [29].

CONCLUSION

Smart contact lenses, through embedded biosensors, antennae and micro-channels, have application in the diagnosis and monitoring of various diseases, as well as ocular drug delivery and therapy, making them important future tools for healthcare systems. Their ability to store data on embedded microchips also presents significant utility for forensic services. However, these devices are expensive and may therefore remain out of reach to many. Moreover, when used long-term for chronic diseases, or with improper handling and maintenance, they can cause dry eyes, allergies, or other side effects. Regarding privacy concerns, SCLs contain personal and intimate user data that can be transmitted to other devices, such as smartphones or smart watches, opening the door to a whole new realm of cybercrimes. The myriad personal data they store could be used against the wearer, potentially affecting their mental status and possibly even resulting in deliberate self-harm. In summary, the deployment of SCLs necessitates a multidisciplinary approach, integrating legal compliance, ethical safeguards, and technological reliability, ensuring that innovation does not outpace protection of user rights and safety.

Table 1. Summary of Key Findings from the Review

Domain	Key Findings	Applications	Advantages	Limitations / Risks
Biosensing: Glucose Monitoring	Tear glucose correlates with blood glucose; real-time monitoring possible	Diabetes diagnosis & continuous monitoring	Non-invasive, painless, continuous data	Accuracy issues, calibration challenges
Biosensing: Intraocular Pressure Monitoring	Sensors detect pressure fluctuations in real time	Glaucoma management	Early detection, continuous monitoring	Sensor stability, long-term wear issues

Domain	Key Findings	Applications	Advantages	Limitations / Risks
Biosensing: Cortisol Detection	Detects stress hormone in tears using graphene-based sensors	Stress monitoring, psychiatric disorders	Highly sensitive, real-time stress analysis	Requires validation, susceptible to environmental interference
Drug Delivery (Theranostics)	Controlled drug release integrated with sensing system	Glaucoma, diabetic retinopathy treatment	Increased bioavailability, reduced dosing frequency	Cost, device complexity
Wireless Data Transmission	Uses RFID/NFC for real-time communication	Remote patient monitoring	Continuous data access, integration with smartphones	Cybersecurity threats, data privacy concerns
Microfluidic System	Capillary-driven tear collection and analysis	Electrolyte, pH, biomarker detection	Accurate, non-invasive sampling	Channel swelling, fluid flow variability
Medicolegal (Cause of Death)	Records physiological parameters before death	Forensic investigation	Timeline reconstruction	Currently theoretical, legal admissibility unclear
Medicolegal (Time of Death)	Tracks last physiological signals (IOP, glucose, temp)	Estimation of time since death	Continuous pre-mortem data	Currently theoretical; requires validation, authentication and assessment of evidentiary reliability
Forensic Evidence (Assault)	Detects stress markers, possible recording features	Crime investigation	Objective physiological data	Privacy concerns, ethical issues, requires legal admissibility
Data Security & Cybercrime	Continuous data storage and wireless transmission	Digital health records	Improved healthcare tracking	Hacking, surveillance misuse
Patient Compliance & Safety	Long-term wear causes discomfort, infection risk	Clinical usability	Non-invasive alternative	Poor compliance, hygiene issues
Economic Factors	High cost (1000–2000 USD)	Limited accessibility	Advanced technology	Affordability barrier

Note. Abbreviations: IOP, intraocular pressure; RFID, radio-frequency identification; NFC, near-field communication.

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