Case Study
ISSN: 3051-8814
Journal homepage: https://www.harrisonacademicpress.com/index.php/FBEMD
Frontiers in Biomedical Engineering and Medical Devices

Harrison Academic Press

Smart Contact Lens Biosensor for Continuous Intraocular Pressure Monitoring in Glaucoma

Russo F[1*], Jansen A[2] and Larsen F[3]

[1]*Department of Biomedical Engineering, University of Padua, Padua, Italy*
[2]*Department of Ophthalmology, Radboud University, Nijmegen, Netherlands*
[3]*Department of Microelectronics, Aarhus University, Aarhus, Denmark*

ABSTRACT

Background: Glaucoma, the leading cause of irreversible blindness, is managed primarily through control of intraocular pressure (IOP), yet standard office tonometry captures only isolated daytime snapshots of a pressure signal that fluctuates continuously, often peaking overnight. Objective: This narrative review synthesizes published literature on smart contact lens biosensors developed to enable continuous, ambulatory IOP monitoring in glaucoma. Methods: We reviewed clinical and engineering studies of the commercially available Sensimed Triggerfish strain-gauge sensor and experimental microfabricated, resonant, and multifunctional contact lens platforms, focusing on transducer design, wireless telemetry, and clinical validation against reference tonometry. Findings: The Triggerfish sensor is safe and well tolerated across repeated 24-hour sessions and detects nocturnal IOP-related dynamics that correlate with visual field progression, though its dimensional output correlates imperfectly with absolute tonometric pressure. Emerging MEMS strain-gauge, resonant LC, and advanced wireless-readout designs report substantially improved sensitivity and, in some cases, quantitative pressure correlation in animal models. Conclusions: Contact lens biosensors have established continuous IOP profiling as clinically feasible, and next-generation sensing and telemetry architectures may extend this capability toward calibrated, multifunctional theranostic monitoring.

Keywords: *intraocular pressure monitoring; smart contact lens biosensor; glaucoma diagnostics; wireless telemetry sensor; continuous ophthalmic monitoring*

Citation: Russo F, Jansen A, Larsen F (2025) Smart Contact Lens Biosensor for Continuous Intraocular Pressure Monitoring in Glaucoma. Front Biomed Eng Med Devices, 3(1): 01-06.
DOI: 10.5281/zenodo.22502679

Corresponding Author: *Federica Russo*

E-mail Address: *federica.russo@universityofpadua.edu*

Article History: *Received 3 January 2025 | Accepted 26 March 2025 | Published 29 June 2025*

Copyright: *© 2025 Federica Russo, et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited (**https://creativecommons.org/licenses/by/4.0/**).*

Introduction

Glaucoma remains the leading cause of irreversible blindness worldwide, with a global prevalence estimated at 3.54% among adults aged 40-80 years and a projected burden of nearly 112 million affected individuals by 2040 [1]. The disease is defined by progressive optic neuropathy in which intraocular pressure (IOP) is the principal modifiable risk factor, and current management is built almost entirely around lowering and stabilizing IOP through medical, laser, or surgical therapy [2]. Yet the clinical assessment of IOP is paradoxically static: office-based Goldmann applanation tonometry captures a single instantaneous value during a brief daytime visit, while IOP itself fluctuates continuously across the 24-hour cycle, peaking most often during nocturnal and early-morning hours when patients are supine and unmonitored [3]. This mismatch between an inherently dynamic physiological signal and a sparse, discontinuous measurement paradigm has motivated three decades of effort toward wearable and implantable sensors capable of ambulatory, continuous IOP telemetry.

Among these approaches, the smart contact lens has emerged as the most clinically mature non-invasive platform. By embedding a strain-sensitive circumferential sensor within a soft, disposable contact lens, such devices exploit the fact that changes in IOP produce measurable changes in corneoscleral curvature at the limbus, without requiring intraocular implantation [3]. The commercial exemplar of this approach, the Sensimed Triggerfish (Sensimed SA, Switzerland), uses a microfabricated platinum-titanium strain gauge embedded in a silicone hydrogel lens to record relative ocular volume changes as a proxy for IOP over a 24-hour wear period, with data transmitted wirelessly to a periorbital antenna and recorder [4]. Over the past decade, this platform and a growing family of experimental strain-gauge, capacitive, and resonant-circuit contact lens sensors have generated a substantial body of clinical and engineering literature. This narrative review synthesizes that literature across three domains: the sensor and transducer technologies

underlying contact lens IOP biosensing, the clinical validation and diagnostic performance data supporting their use, and the wireless telemetry architectures that enable continuous, ambulatory monitoring.

Sensor and Transducer Technologies for Contact Lens IOP Monitoring

The foundational sensing principle for contact lens IOP monitors was established by early work demonstrating that corneal curvature changes associated with IOP elevation could be transduced into an electrical signal using an embedded strain gauge, laying the groundwork for what became the Triggerfish platform [3]. The commercialized device uses a closed annular platinum-titanium strain gauge printed onto a disposable soft contact lens; ocular dimensional changes deform the gauge, altering its electrical resistance in proportion to corneoscleral biomechanical strain rather than to IOP in absolute mmHg units [4]. This distinction—measuring a relative volumetric or dimensional surrogate rather than a calibrated pressure value—has shaped much of the subsequent engineering effort toward alternative transducer designs that could yield quantitative pressure outputs.

Microelectromechanical systems (MEMS) fabrication has enabled several such alternatives. Dou and colleagues developed a wearable contact lens sensor using a MEMS-fabricated platinum strain gauge in a Wheatstone bridge configuration, achieving a sensitivity of 289.5 microvolts per mmHg with favorable dynamic response for continuous monitoring [5]. Similarly, Pang and colleagues fabricated a transparent strain-gauge sensor on a polyethylene terephthalate substrate integrated into a soft lens, reporting a sensitivity of 20 microvolts per mmHg and excellent linearity (R-squared = 0.996) across the clinically relevant 10-30 mmHg range [6]. Beyond resistive strain gauges, resonant inductor-capacitor (LC) circuits have been explored to enable fully passive, battery-free sensing: An and colleagues reported an LC contact lens sensor employing liquid-metal circuit elements that achieved a threefold improvement in sensitivity over prior state-of-the-art contact lens sensors [7]. More recently, Xiao and colleagues combined a PEDOT:PSS-based resistive sensor with a gain-compensated parity-time-symmetric wireless readout to reach a sensitivity of 47.31 ohms per mmHg, roughly fifteen times higher than conventional inductive-coupling approaches, with in vivo correlations to commercial tonometry of R-squared 0.93-0.97 [8].

Multifunctional and theranostic designs represent a further evolution of the field. Kim and colleagues integrated an IOP-sensing strain gauge with a graphene electrode and a drug-eluting reservoir within a single soft contact lens, enabling closed-loop sensing and on-demand pharmacologic IOP reduction in animal models [9]. Liu and colleagues extended this concept toward neuroprosthetic integration, coupling an MXene-based strain sensor (sensitivity 12.52 millivolts per mmHg, with temperature compensation) to a neural stimulation interface capable of driving a sensorimotor feedback loop in animal experiments [10]. Collectively, these transducer innovations illustrate a trajectory from empirically calibrated relative-strain devices toward higher-sensitivity, potentially quantitatively calibrated pressure sensors, though clinical validation of the newer designs in human eyes remains far less extensive than for the commercial Triggerfish platform.

Clinical Validation and Diagnostic Performance

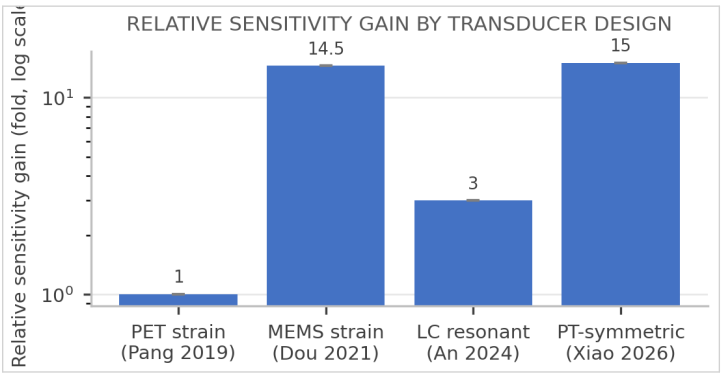
Representative contact lens IOP biosensor platforms: transducer type, reported sensitivity, and validation stage.

Platform	Transducer type	Reported sensitivity	Validation stage
Sensimed Triggerfish	Platinum-titanium strain gauge	Relative dimensional units (uncalibrated to mmHg)	Human clinical, commercial
Dou et al. MEMS lens	MEMS platinum strain gauge, Wheatstone bridge	289.5 uV/mmHg	Bench/ex vivo
Pang et al. PET lens	Transparent PET strain gauge	20 uV/mmHg (R2 = 0.996)	Bench, 10-30 mmHg range
An et al. LC lens	Liquid-metal resonant LC circuit	3x prior state-of-the-art	Bench/animal
Xiao et al. PT-symmetric lens	PEDOT:PSS resistive + PT-symmetric antenna	47.31 Ohm/mmHg (R2 = 0.93-0.97)	Animal model

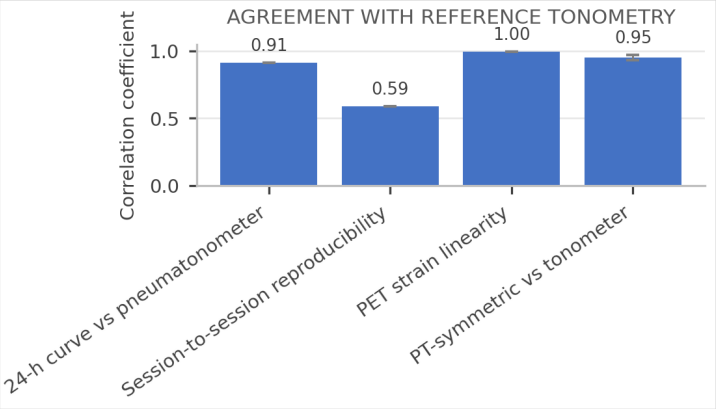
Key clinical studies of contact lens IOP sensors: design, sample, and principal findings.

Study	Population/design	Comparator	Principal finding
Mansouri et al. 2012	40 patients, glaucoma/suspect, two 24-h sessions	Repeat sensor session	Reproducibility r = 0.59; adverse events transient
Mansouri et al. 2015	31 healthy + 2 glaucoma, sleep-lab	Pneumatonometry	Mean 24-h curve R2 = 0.914; pulse detection 86.5%
Liu et al. 2015	30 healthy adults	Pneumatonometry	Peak timing concordant; fluctuation magnitude uncorrelated
De Moraes et al. 2018	Older adults with glaucoma, longitudinal	Goldmann IOP	CLS variables improved prediction of visual field progression
Higashide et al. 2024	79 eyes, normal-tension glaucoma, ~4-y follow-up	Clinical progression	Nocturnal pulse SD, diurnal IOP range predict progression

Relative sensitivity gain of representative contact lens IOP transducers, expressed as fold-change over the earliest transparent strain-gauge design (Pang et al., 2019 = 1x); the Dou et al. (2021) value is derived from each study's reported absolute sensitivity (289.5 vs 20 microvolts per mmHg), while An et al. (2024) and Xiao et al. (2026) values reflect the fold-improvements the authors themselves reported over prior designs. Log scale reflects the order-of-magnitude gains across the design timeline.



Correlation coefficients (R2) reported between contact lens sensor output and reference tonometric/manometric methods across key validation studies, illustrating variable agreement depending on the IOP parameter assessed (mean curve shape versus absolute fluctuation magnitude).



The clinical evidence base for contact lens IOP sensors is dominated by studies of the Sensimed Triggerfish device, reflecting its decade-long regulatory approval and commercial availability. Mansouri and colleagues conducted one of the pivotal safety and reproducibility studies, monitoring 40 patients with glaucoma or glaucoma suspicion across two 24-hour sessions one week apart; the device was well tolerated, with blurred vision (82% of patients) and mild conjunctival hyperemia (80%) as the most common adverse effects, both transient and resolving within 24 hours, and pattern reproducibility between sessions of 0.59, indicating fair-to-good agreement [11]. Building on this safety foundation, Mansouri and colleagues subsequently examined the sensor's capacity to track known 24-hour IOP-related rhythms in healthy volunteers and glaucoma patients monitored in a sleep laboratory, finding a coefficient of correlation between contact lens sensor output and contemporaneous pneumatonometry of R-squared = 0.914 for the mean 24-hour curve, with the sensor also detecting heart-rate-synchronized ocular pulsations with 86.5% accuracy [12]. A companion analysis by Liu and colleagues, however, tempered enthusiasm for absolute quantitative interchangeability: while the timing of the nocturnal IOP peak was statistically indistinguishable between sensor (04:44 AM) and pneumatonometer (04:11 AM) recordings, the magnitude of the estimated fluctuation showed no significant correlation between the two methods, leading the authors to caution that contact lens sensor and tonometric 24-hour IOP estimates should not be treated as interchangeable [13].

Longitudinal outcome studies have sought to establish whether the sensor's dimensional output, rather than a calibrated pressure per se, nonetheless carries prognostic value for glaucomatous progression. De Moraes and colleagues followed older adults with glaucoma and found that regression models incorporating contact lens sensor-derived variables provided a better statistical fit for predicting rates of visual field progression than models based on office Goldmann IOP alone [14]. Higashide and colleagues extended this line of inquiry to normal-tension glaucoma, following 79 eyes for approximately four years and identifying a smaller standard deviation of nocturnal ocular pulse amplitude, a greater diurnal IOP range at baseline, and optic disc hemorrhage during follow-up as significant predictors of progression, concluding that continuous sensor profiles may usefully supplement conventional pressure measurement in risk stratification [15]. Beyond primary glaucoma populations, contact lens sensor monitoring has also been applied to comorbid conditions relevant to IOP regulation: Carnero and colleagues used polysomnography-synchronized contact lens sensor recordings in patients with suspected obstructive sleep apnea syndrome and found that nocturnal IOP elevation plateaus lasted significantly longer in severe disease and correlated with apnea-hypopnea index, implicating nocturnal hypoxic and hemodynamic mechanisms in IOP dysregulation [16]. Across these studies, a consistent picture emerges: the Triggerfish and related contact lens sensors are safe and well tolerated for repeated ambulatory use, provide clinically meaningful pattern-level information about nocturnal and diurnal IOP-related dynamics, and correlate usefully—though imperfectly and non-linearly—with reference tonometric and manometric standards, most authors describing the output as a dimensional or pulse-related surrogate rather than a directly interchangeable pressure value.

Wireless Telemetry and Continuous Monitoring Systems

Continuous ambulatory operation of a contact lens biosensor depends fundamentally on wireless power delivery and data telemetry, since no battery can be safely embedded in a device worn directly on the ocular surface. The Triggerfish architecture addresses this using inductive coupling between an antenna loop embedded in the lens and an external periorbital receiver taped around the eye, which stores raw strain-gauge signals for later offline analysis and IOP-pattern extraction [4,11]. Experimental platforms have pursued more sophisticated readout circuitry to improve range, sensitivity, and dynamic tunability. Chiou and colleagues designed a wirelessly powered smart contact lens system with reconfigurable, wide-range sensor readout circuitry, allowing the capacitive interface to be tuned for sensitivity across different measurement conditions while remaining fully passive and inductively powered [17]. Resonant LC-based architectures, such as that developed by An and colleagues, dispense with active circuitry altogether, encoding pressure-induced strain as a shift in resonant frequency that can be read out remotely via a coupled external coil, an approach that simplifies the implanted or worn component at the cost of readout complexity on the external side [7].

More recent designs have targeted the fundamental trade-off between wireless read range and signal sensitivity. Xiao and colleagues incorporated parity-time symmetry principles, more commonly associated with non-Hermitian physics, into a gain-compensated antenna operating near 70 MHz, substantially amplifying the achievable sensitivity without requiring an onboard power source, and validating the approach against commercial tonometry in animal models with strong correlation coefficients [8]. Multifunctional systems add further telemetry complexity: the theranostic lens of Kim and colleagues required simultaneous wireless sensing and wireless-triggered drug actuation channels within a single passive device [9], while the neuroprosthetic system of Liu and colleagues integrated sensing telemetry with a closed-loop neural stimulation pathway, demonstrating in animal experiments that lens-derived pressure signals could be relayed to modulate a physiological motor response in real time [10]. Taken together, the wireless telemetry literature indicates a clear technical trajectory away from simple inductive data-logging, as used in the clinically validated Triggerfish system, toward higher-sensitivity, lower-power, and increasingly multifunctional readout architectures—though these advanced platforms remain, for now, substantially earlier in translational maturity than the single commercially available continuous IOP contact lens sensor.

Conclusion

Smart contact lens biosensors have transformed the conceptual framework for glaucoma monitoring by making genuinely continuous, ambulatory assessment of IOP-related ocular dynamics clinically feasible for the first time. The Sensimed Triggerfish platform, built on a simple platinum strain-gauge transducer and inductive telemetry, has amassed over a decade of safety, tolerability, and reproducibility data and has demonstrated associations between its 24-hour dimensional profiles and both nocturnal IOP-related physiology and long-term visual field progression [11,12,14,15]. At the same time, the literature is consistent in cautioning that current contact lens sensor outputs represent a relative, dimensional, or pulse-related surrogate for IOP rather than a directly interchangeable quantitative pressure measurement, with correlation to reference tonometry that is robust for some parameters (mean curve shape, pulse timing) but weak for others (absolute fluctuation magnitude) [13]. A vigorous engineering pipeline of MEMS strain gauges, resonant LC circuits, and advanced wireless readout architectures is actively working to close this gap, promising higher sensitivity, quantitative calibration, and multifunctional theranostic capability [5,6,7,8,9,10,17]. As these next-generation devices progress from animal validation toward human clinical trials, continuous contact lens IOP monitoring is well positioned to become an increasingly integral component of individualized glaucoma risk stratification and management.

Acknowledgements

The authors thank colleagues at Department of Biomedical Engineering, University of Padua, Padua, Italy, Department of Ophthalmology, Radboud University, Nijmegen, Netherlands, and Department of Microelectronics, Aarhus University, Aarhus, Denmark for helpful discussions during preparation of this review.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Russo F conceived the review, conducted the literature search, and drafted the manuscript. Jansen A contributed to the literature screening and technical framing and critically revised the manuscript for important intellectual content. Larsen F contributed additional context and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

References

1. Tham YC, Li X, Wong TY, Quigley HA, Aung T, Cheng CY (2014) Global prevalence of glaucoma and projections of glaucoma burden through 2040: a systematic review and meta-analysis. Ophthalmology, 121(11):2081-2090, DOI:10.1016/j.ophtha.2014.05.013.

2. Weinreb RN, Leung CKS, Crowston JG, Medeiros FA, Friedman DS, Wiggs JL, Martin KR (2016) Primary open-angle glaucoma. Nature Reviews Disease Primers, 2:16067, DOI:10.1038/nrdp.2016.67.

3. Kazemi A, McLaren JW, Sit AJ (2015) Continuous 24-hour monitoring of intraocular pressure: emerging technologies. Current Ophthalmology Reports, 3(2):58-66, DOI:10.1007/s40135-015-0066-8.

4. Dunbar GE, Shen BY, Aref AA (2017) The Sensimed Triggerfish contact lens sensor: efficacy, safety, and patient tolerability. Clinical Ophthalmology, 11:875-882, DOI:10.2147/OPTH.S109708.

5. Dou Z, Tang J, Liu Z, Sun Q, Wang Y, Li Y, Yuan M, Wu H, Wang Y, Pei W, Chen H (2021) A wearable contact lens sensor for noninvasive continuous monitoring of intraocular pressure. Micromachines, 12(2):108, DOI:10.3390/mi12020108.

6. Pang Y, Li Y, Wang X, Qi C, Yang Y, Ren TL (2019) A contact lens promising for non-invasive continuous intraocular pressure monitoring. RSC Advances, 9(9):5076-5082, DOI:10.1039/C8RA10257K.

7. An H, Wang X, Liao Z, Zhang L, Zhao H, Yang Y, Song J, Ma Y (2024) LC contact lens sensor for ultrasensitive intraocular pressure monitoring. npj Flexible Electronics, 8:53, DOI:10.1038/s41528-024-00341-z.

8. Xiao T, Zhang H, Takamatsu T, Ashimori A, Azhari S, Kimura K, Miyake T (2026) Ultra-sensitive real-time monitoring of intraocular pressure with an integrated smart contact lens using parity-time symmetry wireless technology. npj Flexible Electronics, 10:4, DOI:10.1038/s41528-025-00507-3.

9. Kim TY, Mok JW, Hong SH, Jeong SH, Choi H, Shin S, Joo CK, Hahn SK (2022) Wireless theranostic smart contact lens for monitoring and control of intraocular pressure in glaucoma. Nature Communications, 13:6801, DOI:10.1038/s41467-022-34597-8.

10. Liu W, Du Z, Duan Z, Li L, Shen G (2024) Neuroprosthetic contact lens enabled sensorimotor system for point-of-care monitoring and feedback of intraocular pressure. Nature Communications, 15:5635, DOI:10.1038/s41467-024-49907-5.

11. Mansouri K, Medeiros FA, Tafreshi A, Weinreb RN (2012) Continuous 24-hour monitoring of intraocular pressure patterns with a contact lens sensor: safety, tolerability, and reproducibility in patients with glaucoma. Archives of Ophthalmology, 130(12):1534-1539, DOI:10.1001/archophthalmol.2012.2280.

12. Mansouri K, Weinreb RN, Liu JHK (2015) Efficacy of a contact lens sensor for monitoring 24-h intraocular pressure related patterns. PLOS ONE, 10(5):e0125530, DOI:10.1371/journal.pone.0125530.

13. Liu JHK, Mansouri K, Weinreb RN (2015) Estimation of 24-hour intraocular pressure peak timing and variation using a contact lens sensor. PLOS ONE, 10(6):e0129529,

DOI:10.1371/journal.pone.0129529.

14. De Moraes CG, Mansouri K, Liebmann JM, Ritch R (2018) Association between 24-hour intraocular pressure monitored with contact lens sensor and visual field progression in older adults with glaucoma. JAMA Ophthalmology, 136(7):779-785, DOI:10.1001/jamaophthalmol.2018.1746.

15. Higashide T, Udagawa S, Nakazawa K, Yamashita Y, Tsuchiya S, Ohkubo S, Sugiyama K (2024) Prediction of glaucoma progression by 24-h contact lens sensor profile in patients with normal-tension glaucoma. Scientific Reports, 14:21564, DOI:10.1038/s41598-024-72556-z.

16. Carnero E, Bragard J, Urrestarazu E, Rivas E, Polo V, Larrosa JM, Anton V, Pelaez A, Moreno-Montanes J (2020) Continuous intraocular pressure monitoring in patients with obstructive sleep apnea syndrome using a contact lens sensor. PLOS ONE, 15(3):e0229856, DOI:10.1371/journal.pone.0229856.

17. Chiou JC, Hsu SH, Huang YC, Yeh GT, Liou WT, Kuei CK (2017) A wirelessly powered smart contact lens with reconfigurable wide range and tunable sensitivity sensor readout circuitry. Sensors, 17(1):108, DOI:10.3390/s17010108.