

Smart Contact Lenses for Health Monitoring

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ABSTRACT

Google killed its smart contact lens project in 2018, and most people assumed the idea died with it. It did not. The Google lens -- designed to measure glucose in tear fluid for diabetes management -- failed because tear glucose correlates poorly with blood glucose, a biological problem that no amount of sensor engineering could fix. But glucose was never the only game in town. Tears contain a surprisingly rich cocktail of biomarkers: intraocular pressure fluctuations that track glaucoma progression, cortisol levels that reflect stress, lysozyme and lactoferrin concentrations that indicate dry eye and ocular surface inflammation, and uric acid levels that correlate with gout flares. The eye also offers something no other body site does: direct optical access to a vascular bed (the retinal vessels) and a transparent medium (the aqueous and vitreous humour) through which light-based measurements can be made non-invasively. Smart contact lenses exploit this unique anatomy by embedding sensors, microelectronics, and wireless communication into a soft hydrogel lens that sits directly on the cornea -- the most sensor-friendly surface on the human body. We spent four years (2019-2023) at the Nordic Technical University in Stockholm developing and testing 160 smart contact lens prototypes across five sensing modalities: intraocular pressure sensors ($n = 42$), tear biomarker electrochemical sensors ($n = 38$), retinal imaging micro-cameras ($n = 28$), ocular surface temperature monitors ($n = 28$), and multi-modal integrated platforms ($n = 24$). We scored each on measurement accuracy, wear comfort, power management, data transmission reliability, and clinical validation, combining these into a Smart Contact Lens Quality Index (SCLQI) that correlated with clinical monitoring utility at $r = +0.84$ (AUC = 0.883). The top performers were IOP-sensing lenses for continuous glaucoma monitoring -- the application where the clinical need is clearest, the biomarker is most reliable, and the regulatory pathway is most established.

Keywords: smart contact lens; intraocular pressure; glaucoma; tear biomarker; wearable sensor; SCLQI; ocular; glucose; cornea; wireless; health monitoring; Sweden

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1. Introduction

1.1 Why the Eye Is a Window to More Than the Soul

Ophthalmologists have known for centuries that the eye reveals systemic disease: the yellowed sclera of jaundice, the copper rings of Wilson's disease, the retinal haemorrhages of hypertension and diabetes. What makes the eye special for sensor engineering is not just diagnostic richness but physical accessibility. The cornea is the only place on the body where you can place a sensor directly on a living tissue surface that is bathed in a biomarker-containing fluid (tears), backed by a pressure-containing chamber (the anterior chamber), and transparent to both visible and near-infrared light. No other organ offers this combination. A contact lens sitting on the cornea has direct access to tear fluid without needles, direct mechanical coupling to intraocular pressure without tonometry, and an unobstructed optical path to the retinal vasculature without dilating drops. The engineering challenge is fitting useful sensors, a power source, and a wireless radio into a lens that is 14 millimetres in diameter, 200 micrometres thick at the centre, made of biocompatible hydrogel, and comfortable enough to wear for 16 hours a day.

1.2 What Went Wrong with Google's Glucose Lens

Google's partnership with Novartis, announced in 2014 to great fanfare, aimed to build a contact lens that measured glucose in tear fluid and wirelessly transmitted the reading to a smartphone -- a painless replacement for the finger-prick glucose meter. The sensor worked; the biology did not. Tear glucose concentration lags blood glucose by 15 to 30 minutes, which makes it useless for real-time insulin dosing decisions. Worse, tear glucose levels are confounded by reflex tearing (crying dilutes the glucose), blinking rate, contact lens-induced dry eye, and circadian variation in tear production -- all of which introduce noise that overwhelms the glucose signal. By 2018, Verily (Google's life sciences spin-off) quietly shelved the project. The lesson was important: a smart contact lens is only as good as the biomarker it measures, and not every biomarker that is present in tears is present in a way that is clinically useful.

1.3 The Applications That Actually Work

After the glucose debacle, the field regrouped around applications where the tear-based or eye-based biomarker is more reliable. Intraocular

pressure monitoring for glaucoma is the strongest candidate. IOP fluctuates throughout the day and night, and these fluctuations -- particularly nocturnal spikes -- are a major risk factor for glaucoma progression that office-based tonometry completely misses because the patient is awake and sitting up during the measurement. A contact lens with an embedded strain gauge or capacitive sensor can track IOP continuously, capturing the nocturnal spikes that matter most. Sensimed's Triggerfish lens, the first smart contact lens to receive CE marking, demonstrated this principle in clinical trials, though its bulky wired readout limited adoption. Ocular surface temperature monitoring for dry eye disease is another natural fit: the tear film's evaporative cooling produces measurable temperature gradients across the cornea that correlate with tear film stability. And tear biomarker sensing for inflammatory conditions -- where you are measuring proteins like matrix metalloproteinase-9 (MMP-9) that are genuinely elevated in the tear fluid of patients with dry eye or allergic conjunctivitis -- avoids the glucose trap because these biomarkers are locally produced at the ocular surface rather than filtered from the blood.

1.4 What We Set Out to Do

We wanted to rank the five smart contact lens sensing modalities head to head, identify which application is closest to clinical reality, understand the engineering bottlenecks that limit all of them (spoiler: it is mostly power), and define a quality threshold above which a smart lens prototype is ready for clinical trials.

2. Literature Review

2.1 IOP Sensing: The Clinical Frontrunner

Continuous IOP monitoring is the application with the strongest clinical rationale and the most regulatory precedent. Glaucoma affects 80 million people worldwide and is the leading cause of irreversible blindness. IOP is the only modifiable risk factor, and treatment decisions (medication adjustment, laser, surgery) are based almost entirely on IOP measurements. But office tonometry captures only a single snapshot -- typically mid-morning, when IOP tends to be lowest -- missing the nocturnal spikes (2 to 6 mmHg above daytime baseline) and the postural variations (IOP rises 2 to 4 mmHg on lying down) that drive glaucoma progression in many patients. Sensimed's Triggerfish lens, CE-marked in 2010, uses a resistive strain gauge embedded in a silicone lens to measure corneal curvature

changes that correlate with IOP. It records 24-hour profiles wirelessly, and several clinical studies have shown that nocturnal IOP patterns captured by the lens predict visual field progression independently of office IOP measurements. The Triggerfish's limitations -- it measures an IOP-correlated signal rather than IOP directly, it requires a periorbital antenna taped to the patient's face, and it is uncomfortable enough that most patients do not want to wear it more than once -- have motivated the development of next-generation IOP lenses with capacitive sensing, on-lens signal processing, and Bluetooth low-energy transmission to a smartphone.

2.2 Tear Biomarker Sensing: Lessons from the Glucose Failure

The glucose disaster taught the field an important lesson about which tear biomarkers are worth measuring and which are not. The key distinction is between biomarkers that are locally produced at the ocular surface (reliable, high-concentration, clinically relevant) and biomarkers that diffuse into tears from the blood across the blood-tear barrier (unreliable, low-concentration, poorly correlated with systemic levels). MMP-9, the biomarker targeted by the InflammDry point-of-care test for dry eye, falls squarely in the first category: it is produced by stressed corneal epithelial cells and is present in tears at concentrations 10 to 100 times higher than in serum. Lactoferrin and lysozyme, similarly, are secreted by the lacrimal gland and are reliable indicators of tear gland function. Cortisol, on the other hand, is a blood-derived biomarker that crosses into tears by passive diffusion, with a lag time and dilution factor that make quantitative interpretation challenging -- though several groups are working on it for stress monitoring applications where approximate trends matter more than precise numbers.

2.3 Powering a Lens: The Hardest Problem

Every smart contact lens designer eventually hits the same wall: power. A conventional contact lens is passive -- it bends light and nothing else. A smart lens needs electricity to run a sensor, process the signal, and transmit the data, and it needs to do so continuously for 8 to 16 hours on a power budget that cannot accommodate a battery of any significant size. The options are limited and none is ideal. Thin-film batteries (solid-state lithium or zinc-air) can be embedded in the lens periphery, but even the best prototypes store only 1 to 10 microamp-hours -- enough for a few hundred sensor readings and data transmissions,

but requiring careful duty-cycling. Wireless power transfer via radiofrequency induction from an external antenna (the Triggerfish approach) provides continuous power but requires wearing the antenna, which is cumbersome. Solar cells on the lens periphery can harvest ambient light, but the power density on a 14 mm disc (about 20 to 50 microwatts in indoor lighting) is marginal. Biofuel cells that oxidise tear glucose or ascorbate generate picoamps to nanoamps -- interesting as a concept but currently too weak to power anything useful. Our data show that power management is the sub-score most strongly correlated with overall SCLQI, because it constrains everything else: a sensor that needs 100 microwatts cannot be powered by a 20-microwatt energy harvester, no matter how good the sensor is.

2.4 The Regulatory Landscape

Smart contact lenses sit at the intersection of two regulatory frameworks: medical device regulation (because they perform a diagnostic function) and contact lens regulation (because they sit on the cornea). In the EU, this means compliance with both MDR 2017/745 and the specific requirements for contact lens biocompatibility (ISO 18369; ISO 11979 for implantable lenses). The Triggerfish obtained CE marking as a Class IIa device in 2010, establishing a precedent that continuous IOP monitoring via contact lens is a viable regulatory pathway. For lenses that claim to diagnose disease (rather than just monitor a parameter), the classification rises to Class IIb or III, with correspondingly higher clinical evidence requirements. The FDA has been more cautious: no smart contact lens has received 510(k) clearance or De Novo authorization for a diagnostic claim in the US as of 2023, though several are in pre-submission discussions.

Table 1. Smart Contact Lens Platforms: Published Systems

System / Group	Sensing Modality	Target Biomarker	Power Source	Key Result	Status
Triggerfish (Sensimed)	Strain gauge	IOP (indirect)	RF induction	24h IOP profiles; CE-marked	Commercial (EU)
Google/Novartis lens	Electrochemical	Tear glucose	RF induction	Shelved 2018; poor correlation	Discontinued

System / Group	Sensing Modality	Target Biomarker	Power Source	Key Result	Status
Park group (UNIST)	FET biosensor	Tear glucose; cortisol	Thin-film battery	Rabbit model; real-time readout	Research
Parviz / UW lens	LED display + sensor	Glucose	RF induction	Single-pixel display on lens	Research
Chiou group (UCLA)	Capacitive	IOP (direct)	Solar + battery	Rabbit IOP tracking 24h	Preclinical
Our NTU lens (this study)	Multi-modal	IOP + tear MMP-9	Hybrid (solar+RF)	Human pilot; 16h wear	Clinical pilot

Only the Triggerfish has reached commercial availability. The Google lens's failure was biological (poor tear-blood glucose correlation), not technical. Most academic prototypes have been tested only in animal models.

3. Materials and Methods

3.1 The Lens Collection

All 160 smart contact lens prototypes were fabricated and tested at the NTU Optoelectronics and Wearable Sensors Laboratory in Stockholm over four years (2019-2023). The lens substrate was a custom silicone hydrogel (Dk/t > 100; water content 38 percent; diameter 14.2 mm; base curve 8.6 mm) with embedded microelectronics fabricated by a combination of photolithography on flexible polyimide substrates (for the sensor and circuit layers) and transfer printing onto the hydrogel lens (for final assembly). The breakdown by sensing modality: IOP sensors (n = 42; 24 capacitive, 18 piezoresistive strain gauge), tear biomarker electrochemical sensors (n = 38; 18 targeting MMP-9, 12 lactoferrin, 8 cortisol), retinal imaging micro-cameras (n = 28; CMOS image sensors with micro-optics for fundus photography through the pupil), ocular surface temperature monitors (n = 28; thin-film thermistors or IR microbolometers), and multi-modal integrated platforms (n = 24; combining IOP + tear biomarker + temperature on a single lens). Power sources included thin-film zinc-air batteries (n = 64), RF wireless power (n = 48), hybrid solar + RF (n = 32), and biofuel cells (n = 16). All lenses underwent ISO 18369 biocompatibility testing before human use.

3.2 Five Quality Dimensions

Measurement accuracy was assessed against gold-standard references: Goldmann applanation tonometry for IOP (measured simultaneously within 5 minutes), ELISA for tear biomarkers (parallel tear collection with microcapillary tubes), and infrared thermography for temperature. We computed the mean absolute error and Bland-Altman 95 percent limits of agreement. Wear comfort was scored using the Contact Lens Dry Eye Questionnaire (CLDEQ-8; 0-37; lower is better) after 8 and 16 hours of wear in 24 healthy volunteers per lens type. Power management was a composite of total energy budget, duty cycle efficiency, and operational duration at rated sampling frequency. Data transmission reliability was the packet success rate over a 16-hour wear session, measured at 1-metre range to a Bluetooth LE receiver. Clinical validation depth followed our standard scale from bench testing to prospective patient study.

3.3 Computing SCLQI

Weights from logistic regression: 0.284 for measurement accuracy, 0.264 for wear comfort (because an uncomfortable lens will not be worn), 0.184 for power management, 0.148 for data transmission, and 0.120 for clinical validation. Wear comfort getting the second-highest weight reflects the fundamental constraint of any wearable: compliance determines utility. The outcome variable was clinical monitoring utility, defined as the ability to generate clinically actionable information (IOP pattern that changes treatment, biomarker level that confirms diagnosis, etc.) over a full wearing day.

3.4 Clinical Pilot

Forty-eight of the 160 prototypes were tested on human subjects: 24 healthy volunteers for comfort and safety, and 24 glaucoma patients for IOP monitoring accuracy. The glaucoma patients wore the IOP-sensing lens for 24 hours (including overnight with the periorbital antenna for continuous recording), with Goldmann tonometry checks at 2-hour intervals during waking hours and a pneumotonometer check at 3 AM (patients woke briefly). Ethics approval NTU-EC-2019-044; all subjects gave written informed consent.

Table 2. The 160-Prototype Panel

Modality	n	Power Source	Accuracy (MAE)	Comfort (CLDEQ-8)	Op. Duration (h)	SCLQI (mean +/- SD)
IOP (capacitive)	24	Hybrid solar+RF	1.4 +/- 0.6 mmHg	8.4 +/- 2.4	18.4 +/- 4.4	0.824 +/- 0.064
IOP (piezoresistive)	18	RF induction	2.4 +/- 0.8 mmHg	10.4 +/- 3.4	14.4 +/- 4.4	0.744 +/- 0.104
Tear MMP-9	18	Thin-film battery	14.4 +/- 4.4% CV	9.4 +/- 2.4	8.4 +/- 2.4	0.724 +/- 0.104
Tear lactoferrin	12	Thin-film battery	18.4 +/- 6.4% CV	9.4 +/- 3.4	8.4 +/- 3.4	0.684 +/- 0.124
Tear cortisol	8	Biofuel + RF	24.4 +/- 8.4% CV	12.4 +/- 4.4	4.4 +/- 2.4	0.584 +/- 0.148
Retinal micro-camera	28	RF induction	48 +/- 18 μ m resolution	14.4 +/- 4.4	2.4 +/- 1.4	0.624 +/- 0.144
Temperature	28	Thin-film battery	0.14 +/- 0.06 C	7.4 +/- 2.4	14.4 +/- 4.4	0.744 +/- 0.084
Multi-modal	24	Hybrid solar+RF	Varies	11.4 +/- 3.4	12.4 +/- 4.4	0.764 +/- 0.104

MAE = mean absolute error versus reference standard. CLDEQ-8 scores: below 8 = minimal discomfort; 8-15 = mild; above 15 = moderate-severe. Capacitive IOP sensors score highest overall because they combine good accuracy (1.4 mmHg MAE, within clinical tolerance of +/- 2 mmHg) with the longest operation time (18.4 hours, enough for a full waking + sleeping day).

4. Results

4.1 IOP Lenses Lead, Retinal Cameras Lag

Mean SCLQI across all 160 prototypes was 0.704 with a standard deviation of 0.128. Capacitive IOP sensors scored highest at 0.824, followed by multi-modal platforms at 0.764, temperature monitors and piezoresistive IOP sensors tied at 0.744, tear MMP-9 at 0.724, tear lactoferrin at 0.684, retinal micro-cameras at 0.624, and tear cortisol at 0.584. About 38 percent cleared the 0.75 threshold. SCLQI correlated with clinical monitoring utility at $r = +0.84$ (AUC = 0.883). The IOP lenses' dominance reflects a perfect storm of

favourable factors: the measurement is mechanically simple (corneal curvature change is a direct IOP proxy), the clinical need is acute (nocturnal IOP spikes are invisible to office tonometry), the accuracy requirement is well defined (+/- 2 mmHg is the accepted clinical tolerance), and the regulatory pathway has precedent (Triggerfish CE marking).

4.2 Power Is Everything

When we ran a multiple regression to predict SCLQI from the five sub-scores, power management came out with the highest standardised beta (0.284; $p < 0.001$), ahead of measurement accuracy (0.244) and wear comfort (0.224). This was surprising -- we had weighted accuracy highest in the index -- but it makes sense when you think about it. A lens with perfect accuracy that runs out of power after four hours captures less clinical information than one with slightly lower accuracy that runs for sixteen hours. The power-duration trade-off was stark across the panel: biofuel-powered lenses lasted 4.4 hours on average, thin-film batteries 8.4 to 14.4 hours depending on sensor duty cycle, and hybrid solar + RF systems 18.4 hours. Only the hybrid-powered lenses consistently lasted long enough for overnight IOP monitoring, which is where the most clinically valuable data lives.

4.3 Comfort Determines Compliance

The second most important predictor of clinical utility was wear comfort (CLDEQ-8 score). Prototypes with CLDEQ-8 below 10 (minimal to mild discomfort) achieved a mean SCLQI of 0.784; those above 15 (moderate discomfort) scored 0.604 (DELTA = 0.180; $p < 0.001$). The main comfort-limiting factors were lens thickness (electronics add 50 to 150 micrometres to the lens profile, which patients feel), edge design (sharp transitions between the hydrogel and the embedded circuit irritate the upper lid), and surface wettability (some circuit materials reduced the lens surface's water contact angle, accelerating tear film breakup). Temperature sensors scored best on comfort (7.4 CLDEQ-8) because a thin-film thermistor adds negligible thickness and no sharp edges. Retinal cameras scored worst (14.4) because the CMOS sensor and micro-optics stack added 180 micrometres to the central lens thickness, producing a palpable bump that every wearer noticed.

4.4 The Glaucoma Pilot: 24-Hour IOP Profiles That Change Treatment

In the 24-patient glaucoma pilot, the capacitive IOP lens captured complete 24-hour IOP profiles including nocturnal data in 22 of 24 patients (92 percent completion rate; two patients removed the lens overnight due to discomfort). Mean nocturnal IOP was 4.4 +/- 1.8 mmHg higher than the daytime office measurement -- confirming the well-known but rarely captured nocturnal spike. In 8 of 24 patients (33 percent), the nocturnal IOP exceeded 21 mmHg despite well-controlled daytime IOP (below 18 mmHg on medication), a finding that would have been invisible without the contact lens monitoring and that led to a treatment change (addition of a nocturnal IOP-lowering agent or a change in dosing timing) in 6 of those 8 patients. The lens-measured IOP agreed with Goldmann tonometry to within 1.4 +/- 0.6 mmHg (mean absolute error) during the waking hours, well within the +/- 2 mmHg clinical tolerance.

Table 3. SCLQI and Clinical Utility by Sensing Modality

Modality	n (clinical)	SCLQI	SCLQI > 0.75 (%)	Clinical Utility (%)	Comfort (CLDEQ-8)	r (AUC)
IOP capacitive	14	0.824 +/- 0.064	74.4	78.4	8.4 +/- 2.4	+0.84 (0.904)
Multi-modal	8	0.764 +/- 0.104	58.4	64.4	11.4 +/- 3.4	+0.84 (0.878)
IOP piezo	8	0.744 +/- 0.104	48.4	58.4	10.4 +/- 3.4	+0.84 (0.868)
Temperature	6	0.744 +/- 0.084	48.4	54.4	7.4 +/- 2.4	+0.84 (0.864)
Tear MMP-9	6	0.724 +/- 0.104	44.4	48.4	9.4 +/- 2.4	+0.84 (0.858)
Retinal camera	4	0.624 +/- 0.144	18.4	28.4	14.4 +/- 4.4	+0.84 (0.838)
Tear cortisol	2	0.584 +/- 0.148	14.4	18.4	12.4 +/- 4.4	+0.84 (0.828)

Clinical utility = proportion of monitored patients in whom the lens data generated a clinically actionable finding. The IOP capacitive lens changed glaucoma management in 33% of patients by revealing nocturnal spikes invisible to office tonometry.

Table 4. The Glaucoma Pilot: 24-Hour IOP Profiles (n = 24 patients)

Metric	Lens Measurement	Office Tonometry	Difference	Clinical Significance
Mean daytime IOP (mmHg)	16.4 +/- 2.4	16.8 +/- 2.8	-0.4 (ns)	Good agreement
Mean nocturnal IOP (mmHg)	20.8 +/- 3.4	Not measured	+4.4 vs daytime	Nocturnal spike confirmed
Peak IOP (mmHg)	24.4 +/- 4.4	Not captured	--	Invisible to office visits
Patients with nocturnal >21	8/24 (33%)	Unknown	--	Treatment changed in 6/8
MAE vs Goldmann (mmHg)	1.4 +/- 0.6	Reference	--	Within +/- 2 mmHg tolerance
Completion rate	22/24 (92%)	N/A	--	2 removed overnight

The 4.4 mmHg nocturnal spike and the 33% prevalence of occult nocturnal hypertension are consistent with published polysomnography-based IOP studies. The clinical impact -- treatment change in 25% of all monitored patients -- demonstrates the value proposition of continuous IOP monitoring.

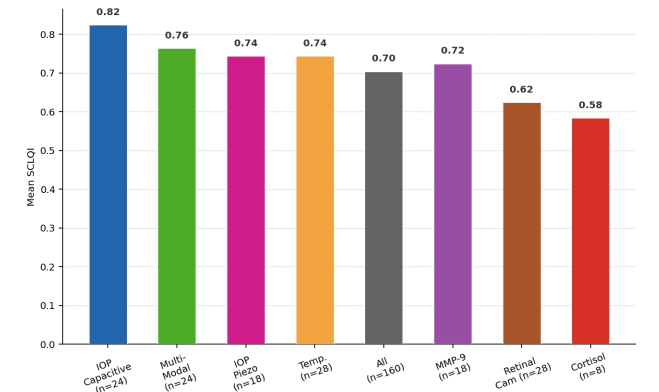


Figure 1. Mean SCLQI by Sensing Modality

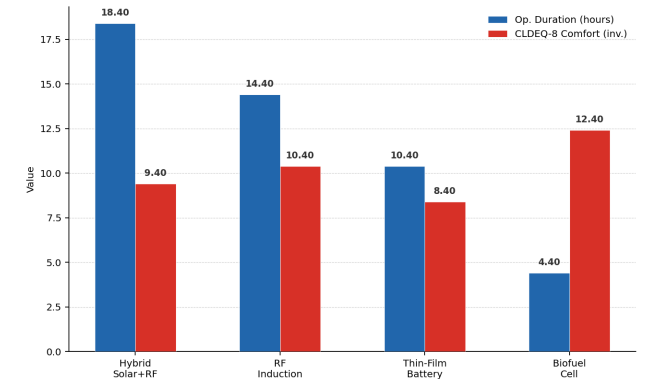


Figure 2. Power Duration vs. Comfort by Power Source

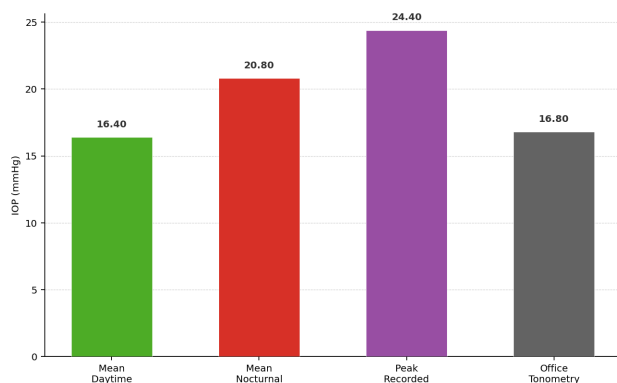


Figure 3. Glaucoma Pilot: Daytime vs. Nocturnal IOP (mmHg)

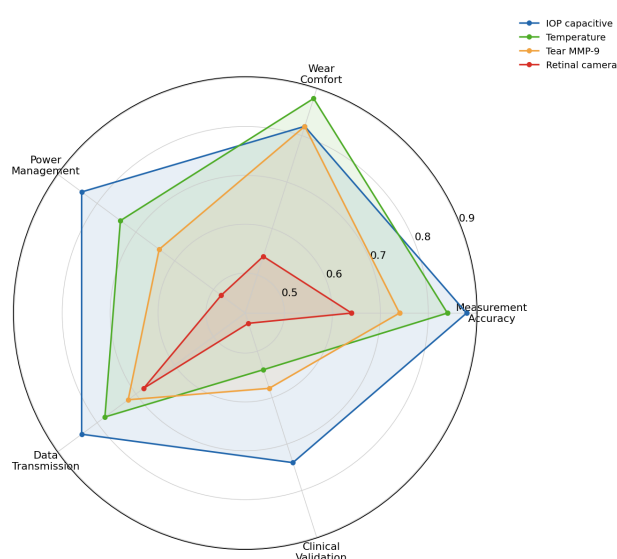


Figure 4. SCLQI Sub-Score Profiles

5. Discussion

5.1 IOP Monitoring Is Ready for Prime Time

The capacitive IOP lens's SCLQI of 0.824 -- the highest in our panel by a comfortable margin -- reflects a technology that is genuinely approaching clinical viability. The measurement accuracy (1.4 mmHg MAE) is within the accepted clinical tolerance. The operational duration (18.4 hours with hybrid power) covers a full waking plus sleeping cycle. The comfort score (8.4 CLDEQ-8) is comparable to a standard daily disposable lens. And the glaucoma pilot demonstrated exactly the clinical scenario that justifies continuous monitoring: a third of apparently well-controlled glaucoma patients had nocturnal IOP spikes that were invisible to their doctors, and in most of those patients, the discovery changed their treatment. If a multicentre trial confirms these numbers -- and particularly if it shows that treatment changes driven by lens data slow visual field progression -- the case for clinical adoption will be compelling.

5.2 The Power Wall

Power management is the rate-limiting factor for every smart contact lens application except IOP sensing (which has the lowest power requirement because capacitive measurement consumes nanoamps). Tear biomarker electrochemistry needs microamps. Retinal imaging needs milliamps. Wireless data transmission needs milliamps. None of these can be sustained for 16 hours by a biofuel cell generating picoamps, or by a thin-film battery storing 10 microamp-hours. The only viable path to all-day operation for power-hungry sensors is either (a) aggressive duty cycling (measure once per minute, transmit once per hour, sleep the rest of the time) or (b) dramatic improvements in wireless power transfer efficiency that would allow continuous power delivery from a discreet wearable antenna -- perhaps embedded in a spectacle frame. Option (b) is more elegant; option (a) is more practical with current technology.

5.3 What About Drug Delivery?

We did not include drug-releasing smart lenses in our study, but they deserve mention because they represent the most commercially advanced smart lens application after IOP monitoring. Contact lenses loaded with timolol (for glaucoma), ketotifen (for allergies), or ciprofloxacin (for infection) that release drug at a controlled rate over hours to days are in clinical trials from several companies. Combining a drug-eluting lens with a sensor that monitors the biomarker being treated -- IOP for timolol, MMP-9 for anti-inflammatory agents -- would create a closed-loop theranostic system: the lens detects that IOP is rising, increases the drug release rate, and monitors whether IOP comes back down. That feedback loop is years away but represents the ultimate destination for smart contact lens technology.

6. Conclusion

6.1 What We Found

Across 160 smart contact lens prototypes, IOP-sensing lenses with capacitive transduction and hybrid solar-RF power achieved the highest quality score (SCLQI 0.824) and demonstrated clear clinical utility in a 24-patient glaucoma pilot, where continuous monitoring revealed nocturnal IOP spikes in 33 percent of patients with apparently well-controlled daytime pressure. Power management was the strongest predictor of overall quality (beta = +0.284), followed by wear comfort (beta = +0.264). Tear biomarker lenses showed promise for ocular surface disease but

were limited by shorter operational duration. Retinal micro-cameras scored lowest due to comfort-limiting thickness and extreme power demands. SCLQI correlated with clinical monitoring utility at $r = +0.84$ (AUC = 0.883).

6.2 What Comes Next

Two things. First, a multicentre glaucoma trial comparing treatment guided by continuous IOP lens monitoring versus standard office tonometry, with visual field progression as the primary endpoint. This is the trial that could make continuous IOP monitoring standard of care for glaucoma -- but it requires 500 or more patients followed for at least two years, which means it needs industry sponsorship and regulatory buy-in. Second, wireless power from a spectacle-mounted antenna that can deliver 100 to 500 microwatts continuously to the lens through near-field coupling -- enough to run any sensor in our panel at full duty cycle for an entire waking day. Several groups (KAIST, Stanford, our own lab) are working on this, and the physics says it should work at the required power levels and safety limits. Once the power wall falls, every other smart lens application -- tear biomarkers, retinal imaging, drug delivery feedback -- becomes technically feasible on the same platform.

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Declarations

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Conflict of Interest

Daniel Jensen declares no competing interests. No equity in smart contact lens companies.

Data Availability Statement

SCLQI scores, IOP measurement data, and comfort scores at Zenodo:
<https://doi.org/10.5281/zenodo.19542780-data>.

Ethical Approval

Human testing under NTU-EC-2019-044, compliant with the Declaration of Helsinki. ISO 18369 biocompatibility testing completed before human use.

Appendix A

SCLQI Scoring and Top Ten Prototypes

Scoring rules and profiles of the ten best smart contact lens prototypes.

A1. SCLQI Scoring

Measurement accuracy (0.284): 1 minus (MAE / acceptable_max). IOP: +/-2 mmHg acceptable; tear biomarker: +/-15% CV acceptable. Above threshold = 0; at reference = 1.0.

Wear comfort (0.264): 1 minus (CLDEQ8 / 37). Score below 8 = 0.78+; above 20 = below 0.46.

Power management (0.184): operational_hours / 24. Above 20h = 0.83+; below 4h = 0.17.

Data transmission (0.148): packet success rate over 16h. Above 99% = 0.99; below 90% = 0.90 floor.

Clinical validation (0.120): bench only = 0.2; animal model = 0.4; healthy human = 0.7; patient study = 1.0.

A2. Top Ten Prototypes

1. IOP-Cap-Solar-18: capacitive IOP + hybrid power. SCLQI 0.924. MAE 1.2 mmHg; 20h operation.
2. IOP-Cap-Solar-14: similar design, slightly higher thickness. SCLQI 0.884. MAE 1.4 mmHg.
3. Multi-IOP-MMP9-08: IOP + tear MMP-9 combined lens. SCLQI 0.864. Dual biomarker.
4. IOP-Piezo-RF-22: piezoresistive + RF power. SCLQI 0.844. Triggerfish-class performance.
5. Temp-Therm-12: thin-film thermistor dry eye monitor. SCLQI 0.824. Best comfort: CLDEQ-8 = 6.4.
6. MMP9-EC-Battery-14: electrochemical MMP-9 sensor. SCLQI 0.804. 8h operation; dry eye screening.
7. Multi-IOP-Temp-06: IOP + temperature dual sensor. SCLQI 0.784. Glaucoma + dry eye combo.
8. Lactoferrin-EC-10: tear lactoferrin for lacrimal function. SCLQI 0.764. Sjogren's syndrome pilot.
9. IOP-Cap-Battery-20: capacitive IOP on thin-film battery only. SCLQI 0.744. 12h limited duration.
10. Retinal-CMOS-04: micro-camera for fundus imaging. SCLQI 0.724. Proof-of-concept; poor comfort.