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Photopic and Mesopic Contrast Sensitivity Changes After Cataract Surgery: Visit-to-Visit AULCSF Reproducibility and Functional Outcomes

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Abstract

Contrast sensitivity captures optical degradation that visual acuity may miss, but its clinical interpretation requires knowledge of test–retest variability and the influence of test conditions. We determined the visit-to-visit minimum detectable change (MDC_{95}) of the area under the log contrast sensitivity function (AULCSF) measured with the imo vifa and compared photopic (high-luminance surround) with mesopic (low-luminance surround) testing in 2,701 eyes of 1,968 patients undergoing cataract surgery at two centers. Visit-to-visit reproducibility was moderate (absolute-agreement intraclass correlation coefficient 0.575; 192 pairs), with an MDC_{95} of 0.540 log units (0.356 after excluding large test–retest discrepancies). AULCSF improved more under photopic than mesopic testing (+ 0.545 vs + 0.269 log units; standardized response mean 1.36 vs 0.86), exceeding the MDC_{95} in 50.5% vs 17.6% of eyes. Within the center performing both conditions, preoperative AULCSF was 0.34 log units lower under photopic testing, the postoperative difference narrowed to − 0.06, and improvement was larger by 0.28 log units (95% CI 0.24–0.32), robust to covariate adjustment. The photopic deficit increased with spatial frequency, consistent with veiling glare from lens scatter. Thus, the magnitude of cataract-related loss and postoperative gain registered by the test differed substantially by surround-luminance condition.

Introduction

Contrast sensitivity describes the visibility of objects across spatial frequencies and captures the cataract-related optical degradation (light scatter and glare disability) that high-contrast visual acuity, which characterizes only the resolution limit of vision, may miss [1, 2]. Because such deficits affect everyday tasks such as face recognition, mobility, and driving, contrast sensitivity is a functional outcome of direct relevance to patients, and cataract surgery is one of the most common settings in which a change in that outcome is expected [2]. Whether a measured change can be interpreted in an individual eye, however, depends on the precision of the test. Traditional contrast sensitivity charts have demonstrated limited test–retest reliability: intraclass correlation coefficients (ICCs) for the Vistech and Functional Acuity Contrast Test of 0.18–0.64 with 95% limits of agreement up to ± 0.85 logCS [3], comparable variability between view-in and wall-chart systems [4], and coefficients of repeatability up to ± 0.47 logCS for a contrast-glare tester in cataract patients [5]. These constraints have hindered routine clinical adoption of contrast sensitivity testing [2].

Computerized adaptive methods such as the quick contrast sensitivity function (qCSF) method estimate the entire contrast sensitivity function in two to five minutes per eye [6–9]. The area under the log contrast sensitivity function (AULCSF) condenses sensitivity across spatial frequencies into a single metric; for qCSF, Hou et al. reported an ICC of 0.974 and detection of a 0.30 log-unit AULCSF change with 94% accuracy [8]. The qCSF method has been validated in amblyopia [7], aging [10], macular disease [11–13], and retinal vascular occlusion [14], detecting deficits missed by visual acuity [12]. The imo vifa provides a rapid ring-target contrast sensitivity test reporting AULCSF under selectable surround

luminance (Supplementary Fig. S1), which makes it possible to ask whether the luminance condition itself changes what the test registers.

In cataract, qCSF detects contrast deficits, particularly at intermediate spatial frequencies, that persist even at visual acuity of 20/25 or better [15], and longitudinal studies show measurable AULCSF improvement in the early postoperative period [16]. In eyes with mild cataract, AULCSF is governed primarily by visual acuity and intraocular straylight [17]. Although intraocular lens design and surgical technique may modulate postoperative contrast sensitivity [18–21], the magnitude of AULCSF change that exceeds expected measurement variability has not been defined. On the imo vifa, a recent report described AULCSF improvement after combined glaucoma–cataract surgery under photopic testing only, without luminance details or reproducibility estimates [22].

Two gaps therefore limit clinical translation. First, no validated MDC_{95} (the change beyond which an observed difference is unlikely to reflect measurement noise) has been established for AULCSF under photopic and mesopic conditions on a clinical instrument; on the imo vifa, reproducibility has been reported only for same-session retests in 25 healthy young adults (AULCSF ICC 0.88–0.97) [23], not for the between-visit variability relevant to clinical follow-up. Second, it is unknown whether high- and low-luminance surround conditions register the cataract-related deficit, and its reversal after surgery, to the same degree. We therefore conducted a two-center study to (1) establish the visit-to-visit MDC_{95} for mesopic and photopic AULCSF; (2) compare the preoperative deficit and the postoperative change under photopic versus mesopic testing; and (3) quantify the magnitude of AULCSF improvement after cataract surgery against the MDC_{95} benchmark and characterize how improvement depends on preoperative function.

Results

The derivation of the two analytic cohorts is shown in Fig. 1, and the baseline characteristics of the cataract surgery cohort are summarized in Table 1.

Table 1
Baseline characteristics of the cataract surgery cohort.

Characteristic	All (n = 2,701)	Mesopic (2,048)	Photopic (653)	P value
Age, mean (SD), y	72.6 (8.9)	72.7 (8.8)	72.3 (9.3)	0.339
Female patients, n/N (%)	1,096/1,968 (55.7)	855/1,529 (55.9)	241/440 (54.8)	0.710
Right eye, n (%)	1,413 (52.3)	1,096 (53.5)	317 (48.5)	0.030
Center, n (%)				**< 0.001**
Koedo Eye Institute	1,784 (66.0)	1,131 (55.2)	653 (100)	
Saitama Medical University	917 (34.0)	917 (44.8)	0 (0)	
Year of surgery, n (%)				**< 0.001**
2019–2022	903 (33.4)	903 (44.1)	0 (0)	
2023–2024	898 (33.2)	898 (43.8)	0 (0)	
2025–2026	900 (33.3)	247 (12.1)	653 (100)	
IOL category, n (%)				**< 0.001**
Monofocal	1,669 (61.8)	1,364 (66.6)	305 (46.7)	
Enhanced monofocal	913 (33.8)	618 (30.2)	295 (45.2)	
Multifocal	119 (4.4)	66 (3.2)	53 (8.1)	
Toric IOL, n (%)	504 (18.7)	343 (16.7)	161 (24.7)	< 0.001
Other concurrent intraocular procedure, n (%)	120 (4.4)	104 (5.1)	16 (2.5)	0.006
Preop CDVA (decimal), median (IQR)	—	0.7 (0.5–0.8)	—	—

AULCSF, area under the log contrast sensitivity function; CDVA, corrected distance visual acuity; CS, contrast sensitivity; IOL, intraocular lens; IQR, interquartile range; SD, standard deviation. Sex is reported at the patient level; other characteristics are reported at the eye level. Photopic measurements were obtained only at Koedo Eye Institute, from 2025 onward. "—" indicates not stratified by luminance, not compared, or not recorded. P values compare mesopic versus photopic eyes, largely independent groups (one shared patient; no eye measured under both conditions), using the Welch t test for age, the Wilcoxon rank-sum test for AULCSF measures and intervals, and the χ^2 test for categorical variables. Preoperative CDVA was recorded only at Saitama Medical University (916 of 917 eyes); at Koedo Eye Institute, testing was restricted to eyes with CDVA ≥ 0.7 (decimal) but acuity at the time of testing was not recorded. Other concurrent intraocular procedures were mainly combined phacovitrectomy (96 eyes). AULCSF values are summarized as median (interquartile range) because their distributions were skewed; the corresponding mean-based comparisons, including the residual difference at equal preoperative AULCSF, are reported in the text and Table 3. Lens-design–specific contrast outcomes are reported separately.

Characteristic	All (n = 2,701)	Mesopic (2,048)	Photopic (653)	P value
Preop AULCSF, median (IQR)	—	1.16 (0.95–1.34)	0.83 (0.62–1.11)	< 0.001
Postop AULCSF, median (IQR)	—	1.41 (1.23–1.58)	1.46 (1.25–1.64)	0.007
ΔAULCSF, median (IQR)	—	+ 0.25 (+ 0.06 to + 0.45)	+ 0.55 (+ 0.27 to + 0.84)	< 0.001
Days preop CS→surgery, median (IQR)	40 (26–63)	43 (26–69)	34 (26–46)	< 0.001
Days surgery→postop CS, median (IQR)	7 (7–20)	7 (6–14)	8 (7–21)	< 0.001

AULCSF, area under the log contrast sensitivity function; CDVA, corrected distance visual acuity; CS, contrast sensitivity; IOL, intraocular lens; IQR, interquartile range; SD, standard deviation. Sex is reported at the patient level; other characteristics are reported at the eye level. Photopic measurements were obtained only at Koedo Eye Institute, from 2025 onward. "—" indicates not stratified by luminance, not compared, or not recorded. P values compare mesopic versus photopic eyes, largely independent groups (one shared patient; no eye measured under both conditions), using the Welch t test for age, the Wilcoxon rank-sum test for AULCSF measures and intervals, and the χ^2 test for categorical variables. Preoperative CDVA was recorded only at Saitama Medical University (916 of 917 eyes); at Koedo Eye Institute, testing was restricted to eyes with CDVA ≥ 0.7 (decimal) but acuity at the time of testing was not recorded. Other concurrent intraocular procedures were mainly combined phacovitrectomy (96 eyes). AULCSF values are summarized as median (interquartile range) because their distributions were skewed; the corresponding mean-based comparisons, including the residual difference at equal preoperative AULCSF, are reported in the text and Table 3. Lens-design–specific contrast outcomes are reported separately.

Visit-to-Visit Reproducibility and MDC_{95}

In the primary visit-to-visit cohort (192 pairs; same-day retests excluded), the combined ICC(A,1) was 0.575 (95% CI, 0.368–0.709; moderate), mean bias + 0.142 log units, and MDC_{95} 0.540 log units (mesopic, 0.491 [156 pairs]; photopic, 0.718 [36 pairs]) (Table 2, Fig. 2). After excluding 32 pairs (16.7%) with an absolute difference ≥ 0.44 log units, ICC(A,1) was 0.782 (95% CI, 0.583–0.874; good) and MDC_{95} 0.356 log units (mesopic 0.356; photopic 0.359). Reliability was highest at intermediate-to-high spatial frequencies and lowest at 1.1 cpd (Supplementary Fig. S2). In an exploratory same-session analysis (399 pairs from 356 eyes), 184 pairs had an initial AULCSF < 0.3 log units; 127 (69.0%) increased to ≥ 0.3 on immediate retesting, whereas 10 crossed in the opposite direction (exact McNemar P < 0.001).

Table 2
Visit-to-visit test–retest reproducibility of AULCSF (same-day retests excluded).

Cohort / subgroup	n	ICC(A,1) (95% CI)	ICC(C,1) (95% CI)	MDC_{95}	Bias	SD
Visit-to-visit, all pairs (primary)						
Combined	192	0.575 (0.368, 0.709)	0.630 (0.537, 0.709)	0.540	+ 0.142	0.276
Mesopic	156	0.528 (0.260, 0.693)	0.604 (0.494, 0.695)	0.491	+ 0.152	0.251
Photopic	36	0.570 (0.307, 0.753)	0.581 (0.316, 0.762)	0.718	+ 0.099	0.366
Visit-to-visit, quality-controlled (sensitivity)						
Combined	160	0.782 (0.583, 0.874)	0.827 (0.770, 0.870)	0.356	+ 0.105	0.182
Mesopic	132	0.725 (0.489, 0.839)	0.779 (0.702, 0.838)	0.356	+ 0.107	0.182
Photopic	28	0.869 (0.695, 0.942)	0.890 (0.777, 0.948)	0.359	+ 0.094	0.183

AULCSF, area under the log contrast sensitivity function; CI, confidence interval; ICC, intraclass correlation coefficient; ICC(A,1), two-way random-effects, absolute-agreement, single-measurement formulation (primary); ICC(C,1), consistency formulation; MDC_{95}, minimum detectable change (1.96 × SD of within-eye differences); SD, standard deviation of within-eye differences (second − first measurement). The 95% limits of agreement equal bias ± 1.96 × SD (primary combined cohort, − 0.398 to + 0.683). Reproducibility was evaluated using visit-to-visit (cross-day, ≤ 29-day) pairs only; same-day intra-session retests were not included in the primary visit-to-visit analysis because they may be affected by first-attempt familiarization (see the exploratory same-session analysis in the Results). The quality-controlled sensitivity analysis excludes 32 pairs with |ΔAULCSF| ≥ 0.44 log units, a cutoff approximating the largest published per-target coefficient of repeatability (≈ 0.47) for a ring-target contrast test in cataract patients [5]; because this criterion is based on the observed test–retest difference, it narrows the distribution by design and is not used for the primary estimate.

AULCSF change after cataract surgery by luminance condition

The application cohort comprised 2,701 eyes from 1,968 patients (mean [SD] age 72.6 [8.9] years; 55.7% of patients female; Table 1). ΔAULCSF was about twice as large under photopic as under mesopic testing: +0.545 (0.401) versus + 0.269 (0.313) log units (difference, + 0.276; 95% CI, + 0.239 to + 0.313; SRM 1.36 vs 0.86) (Table 3). The difference lay in the preoperative value: preoperative AULCSF was 0.26 log units lower under photopic testing (95% CI, − 0.29 to − 0.23), whereas postoperative AULCSF was similar (+ 0.02; −0.01 to + 0.05). ΔAULCSF exceeded the MDC_{95} of 0.540 log units in 50.5% of photopic and 17.6% of mesopic eyes (68.5% and 36.7% against the quality-controlled MDC_{95} of 0.356; 36.0% and 21.9% against the luminance-specific MDC_{95} of 0.718 and 0.491; Supplementary Table S1). Given the

positive retest bias (+ 0.142 log units), the upper 95% limit of agreement (0.683 log units), a conservative one-sided threshold, was exceeded by 38.4% of photopic and 9.8% of mesopic eyes.

Table 3

Preoperative, postoperative, and change in AULCSF by luminance condition in the pooled two-center cohort and within Koedo Eye Institute.

Measure	Pooled two-center cohort			Koedo Eye Institute only		
	Mesopic (2,048)	**Photopic (653)**	**Difference [95% CI]**	**Mesopic (1,131)**	**Photopic (653)**	**Difference [95% CI]**
Preoperative AULCSF	1.125 (0.304)	0.867 (0.340)	−0.258 [−0.291, −0.226]	1.203 (0.275)	0.867 (0.340)	−0.336 [−0.371, −0.302]
Postoperative AULCSF	1.395 (0.248)	1.412 (0.295)	+ 0.017 [−0.011, + 0.046]	1.471 (0.224)	1.412 (0.295)	−0.059 [−0.089, −0.029]
ΔAULCSF	+ 0.269 (0.313)	+ 0.545 (0.401)	+ 0.276 [+ 0.239, + 0.313]	+ 0.268 (0.295)	+ 0.545 (0.401)	+ 0.277 [+ 0.238, + 0.316]
ΔAULCSF, adjusted difference			+ 0.273 [+ 0.237, + 0.309]			+ 0.267 [+ 0.229, + 0.305]
SRM	0.86	1.36	—	0.91	1.36	—
Eyes with ΔAULCSF > MDC_{95}, %	17.6	50.5	—	15.4	50.5	—
Residual difference at equal preoperative AULCSF			+ 0.087 [+ 0.058, + 0.115]			+ 0.015 [−0.016, + 0.047]
Component accounted for by preoperative AULCSF difference			+ 0.189			+ 0.262
ΔAULCSF difference, 2025–2026 only	—	—	—	+ 0.348 (0.326)	+ 0.545 (0.401)	+ 0.197 [+ 0.135, + 0.260]

Measure	Pooled two-center cohort			Koedo Eye Institute only		
	Mesopic (2,048)	Photopic (653)	Difference [95% CI]	Mesopic (1,131)	Photopic (653)	Difference [95% CI]

Values are mean (SD) unless stated; differences are photopic − mesopic with 95% CI from cluster-robust linear regression with patient-level clustering. AULCSF, area under the log contrast sensitivity function; CI, confidence interval; MDC_{95}, minimum detectable change (0.540 log units, primary visit-to-visit estimate); SD, standard deviation; SRM, standardized response mean (mean ΔAULCSF / SD of ΔAULCSF). Adjusted differences are from models including age, intraocular lens category, toric status, and days from surgery to postoperative testing. The residual difference at equal preoperative AULCSF is the coefficient of luminance condition in a regression of ΔAULCSF on condition and preoperative AULCSF; the component accounted for by the preoperative difference is the total difference minus this residual, a descriptive quantity (equivalently, the condition effect on preoperative AULCSF multiplied by the slope of ΔAULCSF on preoperative AULCSF) that does not imply formal causal mediation. In the pooled cohort the residual includes a between-center difference among mesopic eyes (+ 0.129 log units at equal baseline; 95% CI, + 0.106 to + 0.151). Within Koedo Eye Institute, photopic testing became the standard protocol from March 2025, with occasional mesopic testing thereafter; the 2025–2026 row restricts both conditions to eyes operated on in that period (196 mesopic, 653 photopic). Matched-range comparisons are given in Supplementary Table S2.

Within Koedo, where photopic testing became the standard protocol from March 2025, the pattern was the same: preoperative AULCSF was 0.34 log units lower under photopic testing (95% CI, − 0.37 to − 0.30), the postoperative difference narrowed to − 0.06 (− 0.09 to − 0.03), and ΔAULCSF was larger by + 0.28 (+ 0.24 to + 0.32; P < 0.001; SRM 1.36 vs 0.91), essentially unchanged after covariate adjustment (+ 0.27; +0.23 to + 0.31) and within 2025–2026 (+ 0.20; +0.13 to + 0.26) (Table 3). At equal preoperative AULCSF, the residual photopic–mesopic difference was + 0.087 log units (95% CI, + 0.058 to + 0.115) in the pooled cohort but only + 0.015 (− 0.016 to + 0.047; P = 0.35) within Koedo; the pooled residual reflected a between-center difference among mesopic eyes (+ 0.129 at equal baseline; 95% CI, + 0.106 to + 0.151). Thus, approximately 0.26 of the 0.28-log-unit within-center difference was statistically accounted for by the lower preoperative AULCSF observed under photopic testing, and no matched range within Koedo showed a significant residual difference (Supplementary Table S2). Across spatial frequencies, the photopic preoperative deficit increased from − 0.14 log units at 1.1 cpd to − 0.59 at 10.2 cpd, the postoperative difference was near zero at intermediate frequencies (0.00 at 2.8–4.5 cpd), and the photopic excess in change rose from + 0.10 to + 0.42 (Fig. 3). Excluding the 120 eyes with other concurrent procedures did not change the estimates (+ 0.275 pooled; +0.281 within Koedo).

Dependence on Preoperative Function

Within each luminance condition, ΔAULCSF declined monotonically across preoperative AULCSF quartiles (Supplementary Table S1) and across matched absolute ranges (Supplementary Table S2, Supplementary Fig. S3). Under mesopic conditions, mean ΔAULCSF fell from + 0.552 in the worst quartile to + 0.023 in the best; under photopic conditions, from + 0.889 to + 0.153 (P < 0.001 for trend in both). The proportion of eyes exceeding the MDC_{95} fell correspondingly, from 50.7% to 0% under mesopic and from 84.1% to 5.6% under photopic testing.

Discussion

In this two-center study, the same instrument registered a markedly different cataract-related deficit and postoperative change depending on the surround luminance of the test: AULCSF improvement after cataract surgery was about twice as large under photopic (bright-surround) as under mesopic testing, because cataract depressed photopic AULCSF far more whereas the postoperative difference narrowed substantially; the difference persisted within a single center, after covariate adjustment, and within a single calendar period. The visit-to-visit MDC_{95} was 0.54 log units in all eligible visit-to-visit testing and 0.36 log units after removal of large-discrepancy retests; it serves to interpret change in individual eyes, and was exceeded in half of photopic and fewer than one fifth of mesopic eyes.

The primary visit-to-visit ICC(A,1) of 0.575 indicates moderate reliability for all eligible visit-to-visit testing, for which the MDC_{95} of 0.540 is the appropriate benchmark; with pairs with large test–retest differences removed, reliability was good (ICC 0.782) and the MDC_{95} fell to 0.356. Both are within published ranges for established tests (CSV-1000 coefficients of repeatability 0.30–0.93 log units [24, 25], Pelli–Robson 0.14 [24], and a ring-target contrast-glare tester ± 0.47 per target [5]). Prior work has likewise judged treatment-related change against test–retest variability [26]. The positive bias (+ 0.142 log units) and the directional asymmetry of the same-session crossings (127 of 184 low pairs rising above 0.3 versus 10 falling below) are compatible with incomplete task familiarization, although regression to the mean and floor effects may also contribute. MDC_{95} should therefore be regarded as a precision benchmark, not a definitive threshold for surgical response. The bias was not larger under photopic testing (+ 0.099 vs + 0.152 log units for mesopic) and cannot account for the larger photopic improvement.

The monotonic decline in improvement across preoperative strata, seen under both conditions, is compatible with ceiling or headroom effects and may partly reflect regression to the mean, because the outcome incorporates the preoperative measurement used to define the strata.

The larger observed photopic change is consistent with greater sensitivity to the cataract-related deficit rather than evidence of faster recovery: at equal preoperative AULCSF the conditions changed similarly, and the total difference was largely accounted for by the lower photopic preoperative value. At the instrument-setting level, the target's local background was identical and the programmed conditions differed in surround luminance. A bright surround may act as a veiling glare source, such that forward light scatter from a cataractous lens produces greater contrast degradation and removing the opacity yields a larger measured gain. The spatial-frequency profile is consistent with this mechanism, the photopic preoperative deficit growing monotonically with spatial frequency, as expected for forward scatter, and disappearing at intermediate frequencies after surgery. This accords with classic observations that glare light preferentially depresses contrast sensitivity in cataractous eyes through intraocular light scattering [27, 28] and that contrast sensitivity under glare improves after cataract surgery [29]. Practically, bright-surround testing appears to be the more sensitive condition for

documenting cataract-related loss and its surgical reversal, although a within-eye paired comparison is still required to attribute the difference to luminance itself.

Our results extend prior same-session qCSF work [6–8, 10, 30] and the only previous imo vifa report (25 healthy young adults; AULCSF ICC 0.88–0.97) [23] to cross-day testing in a two-center clinical population. Same-session precision has likewise been reported for a computerized chart that was responsive to cataract surgery, whose authors noted that between-day reproducibility remained to be established [31]. The lower visit-to-visit ICC likely reflects between-visit variability, inclusion of all eligible cross-day retests, and a more heterogeneous clinical population, and is the more relevant reference for perioperative change.

Several limitations apply. First, the floor criterion (AULCSF < 0.3) and, at Koedo, the acuity-based indication for testing (≥ 0.7) restrict generalizability to eyes with reasonably preserved function; eyes with very poor preoperative contrast sensitivity or dense cataract are under-represented (the floor criterion removed 1.5% of eligible surgical eyes, with negligible effect in a sensitivity analysis), and acuity at testing was unavailable at Koedo. Second, photopic and mesopic measurements were obtained from different eyes; within Koedo the condition was determined mainly by the timing of a protocol change rather than by patient characteristics, and the difference persisted within 2025–2026, but residual confounding by calendar period cannot be excluded, and because the pooled comparison contained a between-center difference at equal baseline, single-center estimates are emphasized. Third, 16.7% of primary reproducibility pairs differed by ≥ 0.44 log units, so the quality-controlled estimate is a sensitivity analysis defined by the test–retest difference itself, and the photopic reproducibility subgroup was small (n = 36), with wide uncertainty in its MDC_{95}. Fourth, postoperative measurements were obtained at a median of 7 days, reflecting routine early follow-up. Fifth, lens-opacity grading was unavailable.

In conclusion, visit-to-visit reproducibility of AULCSF on the imo vifa yielded an MDC_{95} of 0.54 log units (0.36 under quality-controlled conditions), providing an instrument-specific precision benchmark for interpreting individual-level change. Against this benchmark, the magnitude of cataract-related functional loss and surgical gain registered by the test differed substantially by surround-luminance condition: photopic (bright-surround) testing revealed a larger deficit and about twice the postoperative change of mesopic testing, with a substantially narrowed postoperative difference, a pattern that persisted within a single center and is consistent with veiling glare from lens scatter. Preoperative function remained the most consistent correlate of improvement magnitude. These findings support high-luminance testing for characterizing cataract-related functional change and indicate that the luminance condition should be specified whenever contrast sensitivity is used as a functional outcome.

Methods

Study Design and Ethics

This retrospective study comprised two prespecified analytic cohorts assembled from two ophthalmic centers in Saitama, Japan. The institutional review boards of Koedo Eye Institute (KEI_2026_002) and Saitama Medical University Hospital (H2026-020) approved this retrospective multicenter analysis, including the use of de-identified data from both centers, and the study adhered to the tenets of the Declaration of Helsinki. All methods were carried out in accordance with relevant guidelines and regulations. Given the retrospective design, the requirement for written informed consent was waived by both institutional review boards, and patients were given the opportunity to opt out in accordance with institutional and national guidelines.

Participants and the AULCSF Floor Criterion

Eligible participants were adults (≥ 18 years) undergoing contrast sensitivity measurement at Koedo Eye Institute (May 2022 to May 2026) or Saitama Medical University (January 2024 to February 2026). At Koedo, testing was performed during cataract evaluation and follow-up only in eyes with corrected distance decimal visual acuity of 0.7 (20/30) or better (the reimbursement threshold), and acuity at testing was not separately recorded; at Saitama Medical University, testing was part of routine perioperative evaluation without an acuity restriction, and preoperative corrected acuity was recorded (Table 1). Measurements with AULCSF < 0.3 log units on either occasion were excluded as extreme low values; most such values rose above this threshold on immediate retesting (Results). The criterion removed 2.0% of eligible visit-to-visit pairs and 1.5% of eligible surgical eyes, with minimal effect on the cataract cohort results in a floor-threshold sensitivity analysis.

Instrumentation and AULCSF Measurement

All measurements used the contrast sensitivity module of the imo vifa (CREWT Medical Systems, Tokyo, Japan), a tabletop binocular instrument. Contrast thresholds for a ring (concentric-circle) target were determined by an up-and-down (staircase) procedure at six angular sizes (6.3, 4.0, 2.5, 1.6, 1.0, and 0.64 degrees), corresponding to equivalent spatial frequencies of 1.1, 1.8, 2.8, 4.5, 7.1, and 10.2 cycles per degree, and AULCSF was computed across these frequencies [23]. Testing was monocular with optimal refractive correction. In both conditions the target was presented on a 10 cd/m² local background; the two instrument-defined conditions differed in the luminance of the surrounding field, which was 10 cd/m² (mesopic, low-luminance) or 500 cd/m² (photopic, high-luminance) (Supplementary Fig. S1). Both conditions were measured at Koedo; Saitama Medical University measured only the mesopic condition, and the photopic protocol was introduced at Koedo in 2025. Consequently, photopic and mesopic measurements were obtained largely from different eyes during different periods, precluding within-eye paired comparison.

Reproducibility Cohort

The reproducibility cohort comprised paired AULCSF measurements from the same eye without intervening cataract surgery. Same-day pairs were obtained within a single session; visit-to-visit (cross-day) pairs on separate calendar days within 29 days. The visit-to-visit paradigm was prespecified as the primary clinical reference because it reflects the between-visit variability relevant to longitudinal follow-up, and all visit-to-visit pairs constituted the primary reproducibility cohort. As a sensitivity analysis, pairs with an absolute test–retest difference ≥ 0.44 log units were excluded to characterize reproducibility without large-discrepancy retests; this cutoff approximated the largest published per-target coefficient of repeatability (≈ 0.47 log units) for a ring-target contrast test in cataract patients [5], but, being defined by the test–retest difference itself, it narrows the distribution by design and was not used for the primary estimate.

Cataract Surgery Application Cohort

The application cohort consisted of eyes undergoing phacoemulsification with intraocular lens implantation and paired pre- and postoperative AULCSF (both ≥ 0.3 log units). Eyes undergoing concurrent glaucoma surgery, including minimally invasive glaucoma surgery, were excluded. Eyes undergoing other concurrent intraocular procedures, most commonly combined phacovitrectomy, were retained (120 eyes, 4.4%) and examined in a sensitivity analysis. One eye whose intraocular lens could not be identified was excluded. A discontinued monofocal model (NX-70/NX-70S; 98 eyes, 3.6%) was retained within the monofocal category. This yielded 2,701 eyes from 1,968 patients (1,784 Koedo, 917 Saitama Medical University; Table 1, Fig. 1). Postoperative AULCSF was obtained at routine follow-up, a median of 7 days (interquartile range, 7–20) after surgery, when early functional recovery is typically evident [16].

Statistical Analysis

Reproducibility was quantified by the absolute-agreement ICC [two-way random-effects, single-measurement, ICC(A,1)] with 95% confidence intervals from the F distribution [32]; the consistency formulation [ICC(C,1)] is also reported. ICC magnitudes were classified per Koo and Li as poor (< 0.50), moderate (0.50–0.75), good (0.75–0.90), and excellent (≥ 0.90) [33]. MDC_{95} was computed as 1.96 × the standard deviation of within-eye differences, with Bland–Altman bias and 95% limits of agreement [34], and served as a precision benchmark for individual eyes rather than as an outcome classifier. The primary cataract outcome was the magnitude of improvement (ΔAULCSF = postoperative − preoperative), summarized by mean (SD) overall and by luminance condition, preoperative AULCSF quartile (luminance-specific boundaries), and matched absolute preoperative range. The luminance conditions were compared on the total difference in ΔAULCSF (mean difference and SRM = mean ΔAULCSF / SD of ΔAULCSF) and on its components, preoperative and postoperative AULCSF, by cluster-robust linear regression with patient-level clustering, unadjusted and adjusted for age, intraocular lens category, toric status, and days to postoperative testing. A regression of ΔAULCSF on luminance condition and preoperative AULCSF estimated the residual difference at equal preoperative function; the total difference minus this residual was used as a descriptive estimate of the component statistically accounted for by the condition-specific difference in preoperative AULCSF. Because photopic testing was

available only at Koedo, where it became the standard protocol from March 2025 with occasional mesopic testing thereafter, luminance condition was confounded with center and calendar period; all comparisons were repeated within Koedo and within Koedo eyes operated on in 2025–2026, and coefficients were interpreted as adjusted associations rather than causal effects. The photopic–mesopic difference in ΔAULCSF was also estimated within matched absolute preoperative AULCSF ranges and for each spatial frequency (log contrast sensitivity = $\log_{10}$[1/threshold]). The trend in ΔAULCSF across preoperative strata was tested by cluster-robust regression on stratum rank (P for trend). Baseline characteristics were compared between the mesopic and photopic groups with the Welch t test (age), the χ^2 test (categorical variables), and the Wilcoxon rank-sum test for preoperative, postoperative, and ΔAULCSF, which were skewed (D'Agostino–Pearson $P < 0.001$) and are summarized as median (interquartile range). Robustness was assessed by sensitivity analyses of the reproducibility estimates, by applying luminance-specific MDC_{95} values, and by repeating the cataract analyses without the 120 eyes with other concurrent procedures. An exploratory post hoc analysis of same-session pairs (floor criterion not applied) compared the direction of crossing of the 0.3-log-unit threshold between first and repeat measurements (exact McNemar test). Analyses used Python 3.11 (SciPy, statsmodels); two-sided $P < 0.05$ was significant.

Use of generative artificial intelligence

Generative artificial intelligence tools (Claude, Anthropic, San Francisco, CA; ChatGPT, OpenAI, San Francisco, CA) were used for language editing, manuscript formatting, pre-submission consistency checking, and assistance with coding and numerical verification of statistical analyses specified by the authors. The study design, analysis plan, analytic decisions, and interpretation were determined by the authors, who reviewed all AI-assisted outputs and take full responsibility for the manuscript.

Declarations

Code availability

Custom Python scripts used for the statistical analyses and figure generation are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing interests. No author has a proprietary or financial interest in the imo vifa or in CREWT Medical Systems.

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management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Author Contribution

KY, TN and TS conceived and designed the study. KY, TK, KS and SO acquired and curated the data. TS performed the statistical analyses and prepared the figures. TN and KSh supervised the study and contributed to interpretation. KY and TS drafted the manuscript. All authors critically revised the manuscript, and read and approved the final version.

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Data Availability

The de-identified patient-level data supporting the findings of this study are not publicly available because they contain clinical information governed by institutional ethics approvals. They are available from the corresponding author upon reasonable request, subject to approval by the relevant institutional review boards and applicable privacy regulations.

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Figures

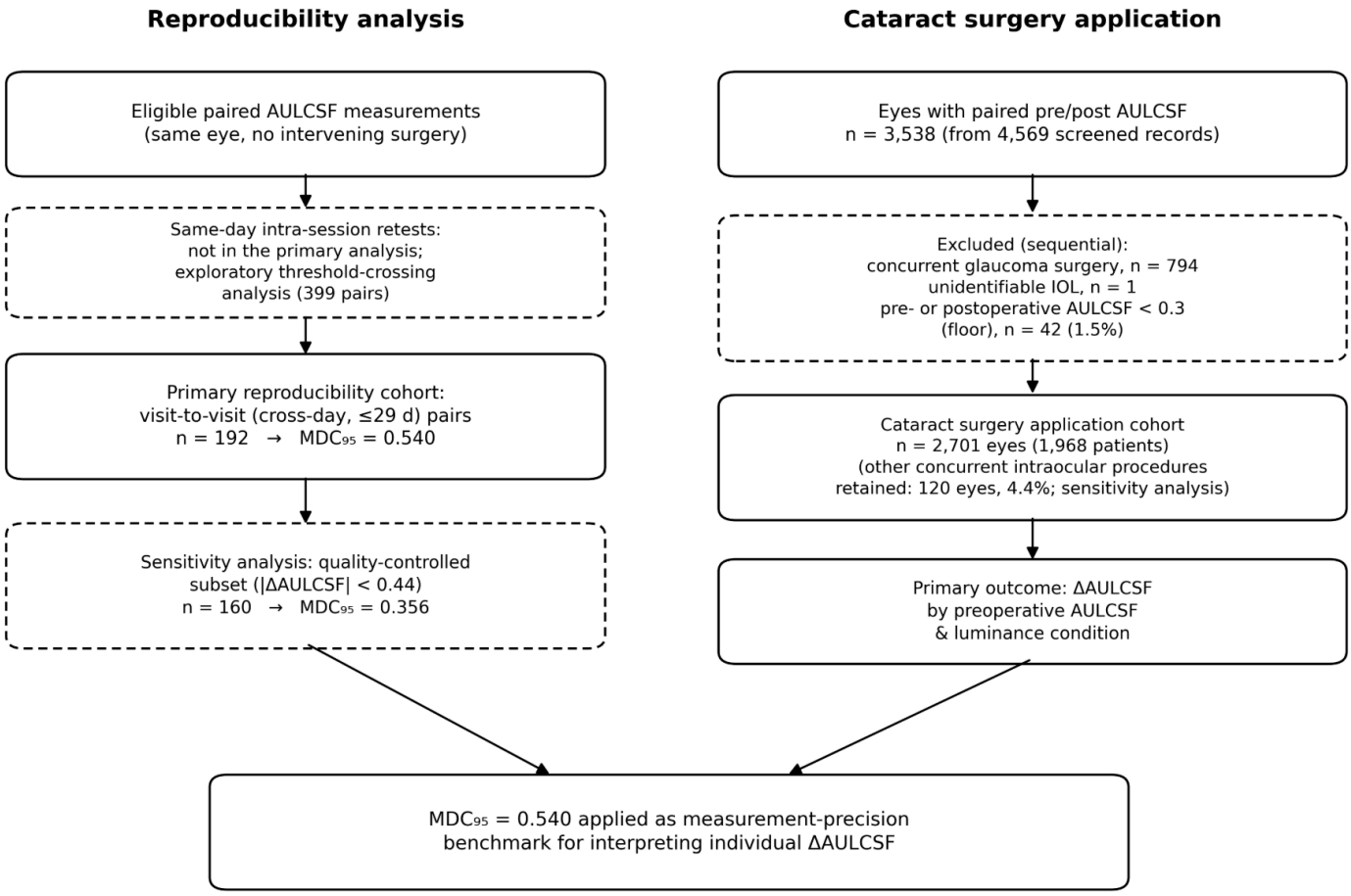


Figure 1

Study flow diagram.

Derivation of the two analytic cohorts. Left: the reproducibility cohort; all visit-to-visit pairs form the primary cohort, the quality-controlled subset (|ΔAULCSF| <0.44) is a sensitivity analysis, and same-session pairs are used only in the exploratory threshold-crossing analysis. Right: the cataract surgery application cohort (2,701 eyes) after sequential exclusion of eyes without paired measurements, concurrent glaucoma surgery, an unidentifiable IOL, and floor-level AULCSF. The MDC_{95} = 0.540 derived from the primary visit-to-visit cohort is used as a measurement-precision benchmark in the surgical cohort.

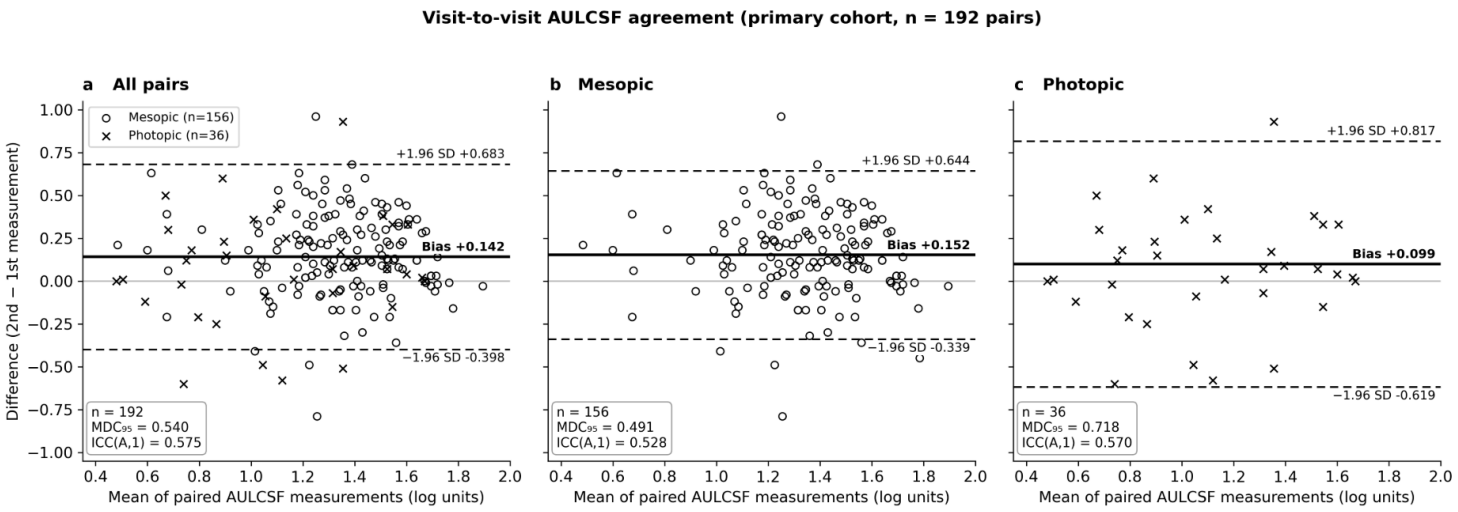


Figure 2

Bland–Altman analysis of visit-to-visit AULCSF test–retest reproducibility.

Agreement between paired visit-to-visit measurements in the primary cohort (192 pairs): (**a**) all pairs, (**b**) mesopic pairs (n=156), and (**c**) photopic pairs (n=36). Solid line, mean bias; dashed lines, 95% limits of agreement; the bias, limits of agreement, and MDC_{95} are annotated in each panel. A positive bias was present in all subsets; MDC_{95} was 0.540 (combined), 0.491 (mesopic), and 0.718 (photopic) log units.

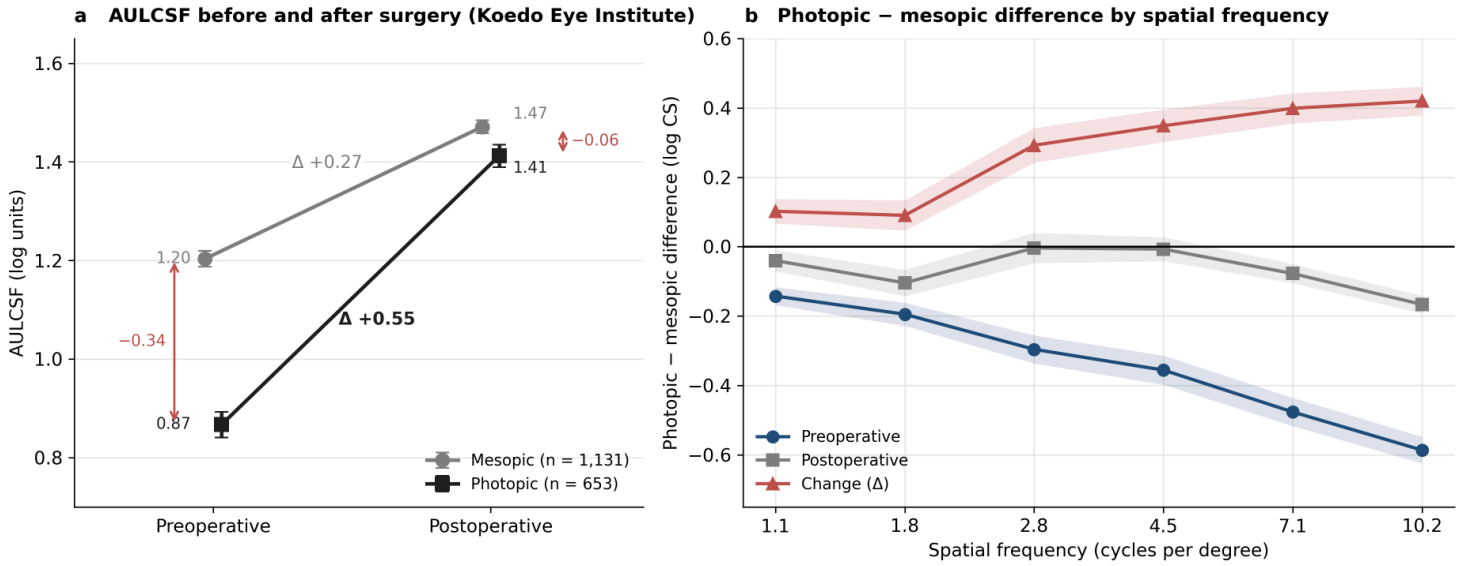


Figure 3

Preoperative and postoperative contrast sensitivity by luminance condition within Koedo Eye Institute.

(**a**) Mean AULCSF before and after cataract surgery under mesopic (n=1,131) and photopic (n=653) testing, with 95% confidence interval whiskers, the mean change (Δ) labeled on each line, and the photopic − mesopic difference (red arrows) shown before and after surgery: the preoperative value is

0.34 log units lower under photopic testing, whereas the postoperative difference narrows to −0.06, so the change is about twice as large. (**b**) Photopic − mesopic difference at each spatial frequency (log contrast sensitivity; 95% confidence bands) for the preoperative value, the postoperative value, and the change: the preoperative deficit under photopic testing increases with spatial frequency, the postoperative difference is small (near zero at 2.8–4.5 cycles per degree), and the photopic excess in change rises accordingly.

Supplementary Files

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- Additionalfile1TablesS1S2v36.pdf
- Additionalfile2FiguresS1S3v36.pdf