

Association of Cumulative Dissipated Energy with Early Postoperative Corneal Edema Following Phacoemulsification: A Prospective Observational Study

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ABSTRACT

Background: Early corneal edema after phacoemulsification reflects postoperative disturbance of corneal hydration and may be associated with intraoperative endothelial stress. Cumulative dissipated energy (CDE) is a device-generated index of ultrasound use. This study examined the association of CDE with day-1 corneal edema, central corneal thickness (CCT) changes, and day-30 endothelial cell loss.

Methods: In this prospective observational cohort, 120 eyes of 120 patients underwent uncomplicated longitudinal phacoemulsification by one surgeon. CDE was recorded intraoperatively; CCT was evaluated before surgery and on postoperative days 1, 7 and 30. Day-1 edema was graded 0–4, with grade ≥2 prespecified as clinically significant; endothelial cell density (ECD) was reassessed on day 30. Associations were evaluated using Spearman correlation, multivariable linear and logistic regression, and receiver operating characteristic (ROC) analysis.

Results: Mean CDE was 8.58 ± 4.33 %-s. Mean CCT increased by 56.7 ± 25.9 µm (10.7%) on day 1 and was close to baseline by day 30. Day-1 CCT increases were 38.2, 52.7 and 79.2 µm across ascending CDE tertiles (p < 0.001). Clinically significant edema occurred in 52 eyes (43.3%): 8/40 (20.0%), 14/40 (35.0%) and 30/40 (75.0%) across tertiles (p < 0.001). CDE correlated with day-1 CCT change (Spearman ρ = 0.71; p < 0.001). After adjustment, each 1 %-s increase in CDE was associated with 4.14 µm greater day-1 CCT change (95% CI 2.91–5.37) and higher odds of grade ≥2 edema (adjusted OR 1.37; 95% CI 1.11–1.70). Lower preoperative ECD was also associated with the primary outcome; diabetes was associated with greater continuous CCT change but not significantly with grade ≥2 edema. Apparent discrimination by CDE was moderate (AUC 0.78; 95% CI 0.69–0.86); the sample-derived 8.4 %-s cut-off yielded 71.2% sensitivity and 73.5% specificity. Higher CDE was associated with greater day-30 endothelial cell loss.

Conclusion: Within this cohort, higher CDE was independently associated with more marked early postoperative corneal swelling and one-month endothelial cell loss. The proposed CDE threshold is exploratory and requires validation before use for individual treatment decisions.

Keywords: cumulative dissipated energy; phacoemulsification; corneal edema; central corneal thickness; corneal endothelial cell density; cataract surgery

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INTRODUCTION

Phacoemulsification is a widely performed procedure for cataract extraction. Transient corneal edema is a recognized early postoperative finding that can delay visual recovery, whereas persistent decompensation may cause substantial visual morbidity (1,2). Corneal hydration is controlled by endothelial barrier and pump function; postoperative thickening can therefore provide an indirect measure of endothelial stress, although inflammation and other mechanisms may also contribute (2,3).

During phacoemulsification, the endothelium may be exposed to cavitation-related free radicals, heat, fluid turbulence and contact with lens fragments (3,4). The magnitude of corneal injury is influenced by nuclear density, preoperative endothelial reserve, ultrasound use, irrigation dynamics and patient-related factors. Contemporary comparative studies have observed associations among surgical energy requirements, early corneal edema and endothelial outcomes (5,6). Diabetes may further impair postoperative endothelial recovery, as demonstrated in a recent meta-analysis (7,8).

Cumulative dissipated energy (CDE) is a machine-calculated index that integrates ultrasound exposure and amplitude/power over time. For longitudinal operation, the reported value is commonly expressed in percent-seconds (%-s); it should not be equated directly with physical energy in joules or assumed comparable across all ultrasound modalities and platforms (9,11,12). Higher CDE is often associated with denser cataracts and aspects of surgical technique (9). Changes in central corneal thickness (CCT) on day 1 have also been associated with later endothelial cell loss (10).

Although CDE and postoperative endothelial outcomes have been examined, the extent to which CDE is associated with a defined clinical grade of early edema after accounting for nuclear grade and preoperative endothelial cell density (ECD), and whether a cohort-specific CDE cut-off offers useful discrimination, merit further evaluation. We therefore examined (1) the association of CDE with day-1 CCT change, (2) its adjusted association with grade ≥ 2 day-1 edema, (3) the apparent discriminatory performance of a CDE threshold, and (4) CCT recovery and endothelial cell loss through day 30.

METHODS

Study design and ethics

This prospective observational cohort study was conducted from December 2023 to June 2024 evaluated consecutive adults undergoing cataract surgery. One eye per patient was included. The study protocol received institutional review board approval, followed the Declaration of Helsinki, and included written informed consent from all participants. Reporting was guided by the STROBE recommendations for observational cohort studies.

Participants

Adults aged 40 years or older with age-related cataract scheduled for phacoemulsification and in-the-bag intraocular lens (IOL) implantation were screened consecutively. If a participant underwent surgery in both eyes during the study period, only the first operated eye was included. The exclusion criteria were preoperative ECD below 1500 cells/mm²; corneal guttae, Fuchs endothelial dystrophy or other corneal disease; previous intraocular or corneal surgery; glaucoma or intraocular pressure above 21 mmHg; pseudoexfoliation; uveitis; traumatic, posterior polar or white mature cataract; axial length below 21 mm or above 26.5 mm; contact lens wear within two weeks; and intraoperative complications or deviation from the planned technique, including posterior capsule rupture, vitreous loss, iris prolapse, Descemet membrane detachment and wound burn.

Preoperative measurements

Preoperative assessment comprised best-corrected visual acuity (BCVA, recorded as logarithm of the minimum angle of resolution [logMAR]), slit-lamp examination, Goldmann applanation tonometry and dilated funduscopy. Lens nuclear opalescence was graded by one masked observer using the Lens Opacities Classification System III (LOCS III); the study included grades 2–6. The LOCS III nuclear opalescence score expresses increasing nuclear density on its ordinal photographic-reference scale (15). Axial length and anterior chamber depth (ACD) were measured by optical biometry. CCT was summarized from three pachymetric readings. Central ECD was assessed by noncontact specular microscopy using at least 75 contiguous endothelial cells. Diabetes and hypertension were recorded from medical history.

Surgical procedure and intraoperative measures

One experienced surgeon performed all procedures under topical anesthesia using longitudinal phacoemulsification with a 0.9-mm, 45° tip. A 2.2-mm temporal clear corneal main incision and one side port were created. Following cohesive and dispersive ophthalmic viscosurgical device application using a soft-shell approach, a 5.0–5.5-mm continuous curvilinear capsulorhexis and hydrodissection were performed. Nuclear disassembly was accomplished using divide-and-conquer or stop-and-chop, selected by the surgeon. The same phacoemulsification settings were maintained throughout the study. Cortex was removed by bimanual irrigation and aspiration; a hydrophobic acrylic IOL was implanted in the capsular bag. The ophthalmic viscosurgical device was removed, wounds were hydrated and intracameral moxifloxacin was administered. Postoperative treatment comprised topical moxifloxacin four times daily for one week and prednisolone acetate 1% tapered over four weeks; hypertonic saline was not used during the study.

CDE (%-s), total ultrasound time (seconds), aspiration time (seconds) and balanced salt solution (BSS) volume (mL) were transcribed from the machine display at the end of surgery by an assistant who was not involved in postoperative grading. Operative duration was measured from incision to wound hydration. Because CDE is a platform-derived ultrasound exposure index, its unit and interpretation are restricted to the reported longitudinal settings (11,12).

Follow-up and outcomes

Patients were reassessed on postoperative days 1, 7 and 30. CCT was measured using the same protocol as at baseline, at approximately the same time of day. A postoperative examiner masked to intraoperative CDE graded day-1 corneal edema at the slit lamp: grade 0, clear cornea; grade 1,

trace localized edema; grade 2, mild diffuse stromal haze; grade 3, moderate stromal edema with Descemet folds; and grade 4, severe edema with epithelial bullae. BCVA was evaluated on days 1 and 30, and specular microscopic ECD was repeated at day 30.

The primary outcome was clinically significant day-1 corneal edema (grade ≥ 2). Secondary outcomes were absolute day-1 CCT change [$\Delta\text{CCT} = \text{day-1 CCT} - \text{preoperative CCT}$ (μm)], relative CCT increase [$100 \times \Delta\text{CCT} / \text{preoperative CCT}$ (%)], CCT at days 7 and 30, BCVA at days 1 and 30, and day-30 percentage endothelial cell loss [$\text{ECL} = 100 \times (\text{preoperative ECD} - \text{day-30 ECD}) / \text{preoperative ECD}$].

Sample size

For an anticipated correlation of 0.30 between CDE and ΔCCT , the Fisher-z approximation at a two-sided α of 0.05 and 80% power gives approximately 85 eyes. The planned sample was increased to 120 to allow multivariable analysis and estimation of clinically significant edema frequency. The final sample contained 52 primary-outcome events; multivariable odds-ratio estimates should therefore be interpreted with consideration of model size and precision.

Statistical analysis

Eyes were categorized into CDE tertiles using the observed distribution: low ($\leq 5.94\%$ -s), medium (5.95–9.70 %-s), and high ($> 9.70\%$ -s), with 40 eyes in each group. Continuous variables were summarized as mean $\pm$ standard deviation (SD), and categorical variables as number (percentage). Between-tertile comparisons used one-way analysis of variance for continuous outcomes and chi-square tests for categorical outcomes; Kruskal–Wallis testing was used as a distribution-robustness check, with Bonferroni-adjusted Mann–Whitney U tests for selected pairwise comparisons. The Friedman test and corrected Wilcoxon signed-rank tests compared serial CCT measurements with baseline. Spearman correlation assessed monotonic associations.

A multivariable linear model examined day-1 ΔCCT in relation to CDE, age, diabetes, LOCS III nuclear opalescence grade, baseline ECD, baseline CCT, BSS volume and nucleus-disassembly technique. Regression coefficients (B) and 95% confidence intervals (CIs) were reported. The logistic model for day-1 edema grade ≥ 2 included CDE, baseline ECD (per 100 cells/ mm^2), diabetes, LOCS III grade, BSS volume and age; results were expressed as adjusted odds ratios (ORs) with 95% CIs. Model diagnostics included variance inflation factors, assessment of residual distribution and heteroscedasticity-consistent (HC3) standard errors for the linear model, and the Hosmer–Lemeshow test for the logistic model. Ultrasound time was excluded from the CDE-adjusted models because of near-collinearity with CDE ($r = 0.97$).

Apparent discrimination of CDE for grade ≥ 2 edema was estimated by ROC area under the curve (AUC). The originally reported AUC 95% CI was calculated from 2,000 bootstrap resamples; the threshold was chosen by the Youden index on the study sample. The reported threshold performance represents in-sample classification and is not external validation. Two-sided $p < 0.05$ was the significance criterion. Analyses used Python 3 (SciPy, statsmodels and scikit-learn).

RESULTS

Participant characteristics and operative measures

The analysis comprised 120 eyes of 120 patients who completed 30-day follow-up. Mean age was 62.4 ± 9.1 years (range 41–85); 62 patients (51.7%) were men, 35 (29.2%) had diabetes, and 46 (38.3%) had hypertension. Mean CDE was $8.58 \pm 4.33\%$ -s (range 2.28–23.69). Baseline age, sex, axial length, ACD, CCT and ECD did not differ significantly among tertiles (Table 1). Higher tertiles had greater nuclear opalescence scores, worse preoperative BCVA and longer operative ultrasound/aspiration measures. CDE correlated strongly with LOCS III grade ($\rho = 0.83$; $p < 0.001$); mean CDE ranged from 3.32 %-s at grade 2 to 14.74 %-s at grade 6. Mean CDE was numerically lower with stop-and-chop than divide-and-conquer (7.73 ± 3.88 versus $9.31 \pm 4.59\%$ -s; reported $p = 0.050$).

Table 1. Baseline characteristics and operative measures according to CDE tertile.

Variable	All (n = 120)	Low CDE (n = 40)	Medium CDE (n = 40)	High CDE (n = 40)	p
Age, years	62.4 ± 9.1	61.0 ± 8.2	63.4 ± 9.7	62.8 ± 9.4	0.481
Male sex, n (%)	62 (51.7)	17 (42.5)	20 (50.0)	25 (62.5)	0.195
Right eye, n (%)	64 (53.3)	18 (45.0)	20 (50.0)	26 (65.0)	0.175
Diabetes, n (%)	35 (29.2)	10 (25.0)	10 (25.0)	15 (37.5)	0.365
Hypertension, n (%)	46 (38.3)	14 (35.0)	16 (40.0)	16 (40.0)	0.868
Axial length, mm	23.41 ± 0.88	23.5 ± 1.0	23.4 ± 0.7	23.4 ± 0.8	0.825
ACD, mm	3.01 ± 0.35	3.01 ± 0.34	2.98 ± 0.36	3.03 ± 0.36	0.769
LOCS III NO grade	3.8 ± 1.2	2.8 ± 0.7	3.9 ± 0.8	4.9 ± 0.8	<0.001
Preop BCVA, logMAR	0.49 ± 0.18	0.35 ± 0.12	0.52 ± 0.15	0.61 ± 0.16	<0.001
Preop CCT, μm	532.6 ± 25.7	534.2 ± 28.1	530.7 ± 23.7	533.1 ± 25.7	0.826
Preop ECD, cells/ mm^2	2477 ± 246	2500 ± 247	2467 ± 283	2464 ± 207	0.771

Variable	All (n = 120)	Low CDE (n = 40)	Medium CDE (n = 40)	High CDE (n = 40)	p
Stop-and-chop, n (%)	55 (45.8)	21 (52.5)	20 (50.0)	14 (35.0)	0.236
CDE, %-s	8.58 ± 4.33	4.3 ± 1.2	7.9 ± 1.1	13.6 ± 3.1	<0.001
Total US time, s	25.2 ± 13.7	12.5 ± 3.9	22.6 ± 4.4	40.5 ± 11.4	<0.001
Aspiration time, s	138.6 ± 50.2	98.2 ± 19.9	129.0 ± 23.2	188.6 ± 49.1	<0.001
BSS volume, ml	53.0 ± 10.2	45.4 ± 8.1	53.1 ± 7.7	60.6 ± 8.6	<0.001
Surgery duration, min	17.2 ± 3.0	15.6 ± 2.9	16.9 ± 2.8	18.9 ± 2.3	<0.001

Table 1 note. Values are mean ± SD or n (%), as indicated. The p values are the reported one-way ANOVA or chi-square results. CDE tertiles: low ≤5.94 %-s; medium 5.95–9.70 %-s; high >9.70 %-s. NO, nuclear opalescence; US, ultrasound; BSS, balanced salt solution; ACD, anterior chamber depth.

Corneal thickness and day-1 edema

Mean CCT increased from 532.6 ± 25.7 µm preoperatively to 589.3 ± 37.0 µm on day 1 (ΔCCT 56.7 ± 25.9 µm; mean increase 10.7 ± 4.9%) and then declined to 549.3 ± 28.2 µm on day 7 and 534.2 ± 26.4 µm on day 30 (Friedman p < 0.001). The reported mean day-30 residual change was 1.5 µm (95% CI 0.7–2.4 µm), small in clinical magnitude; 118/120 eyes (98.3%) had CCT within 2% of their individual baseline values. Day-1 mean ΔCCT rose across low, medium and high CDE tertiles (38.2, 52.7 and 79.2 µm; between-group p < 0.001); the corresponding day-7 residual changes were 10.7, 16.0 and 23.2 µm (Figure 1).

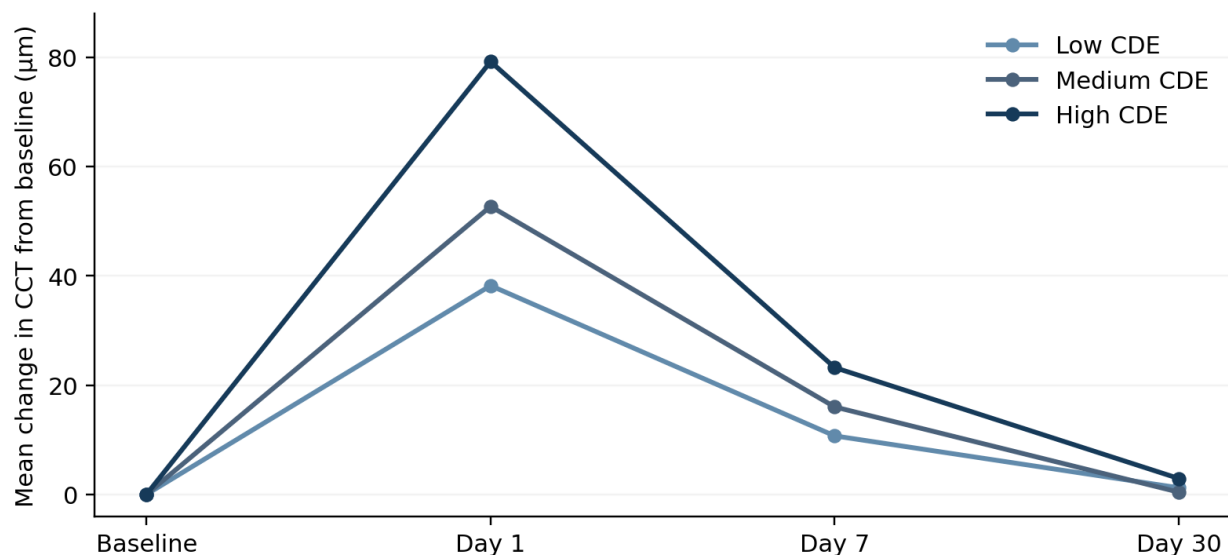


Figure 1. Mean CCT change relative to baseline by CDE tertile (n = 40 per tertile). Aggregate means are plotted without confidence intervals because paired longitudinal variance estimates are not supplied by the source summary.

Day-1 grade ≥2 edema occurred in 52 eyes (43.3%), comprising 39 eyes with grade 2, 12 with grade 3 and one with grade 4. The frequencies were 8/40 (20.0%), 14/40 (35.0%) and 30/40 (75.0%) across ascending CDE tertiles (p < 0.001; Figure 2). The single grade-4 eye had CDE of 14.4 %-s and day-1 ΔCCT of 102 µm; this eye returned to its baseline thickness by day 30. Postoperative outcomes by tertile are summarized in Table 2.

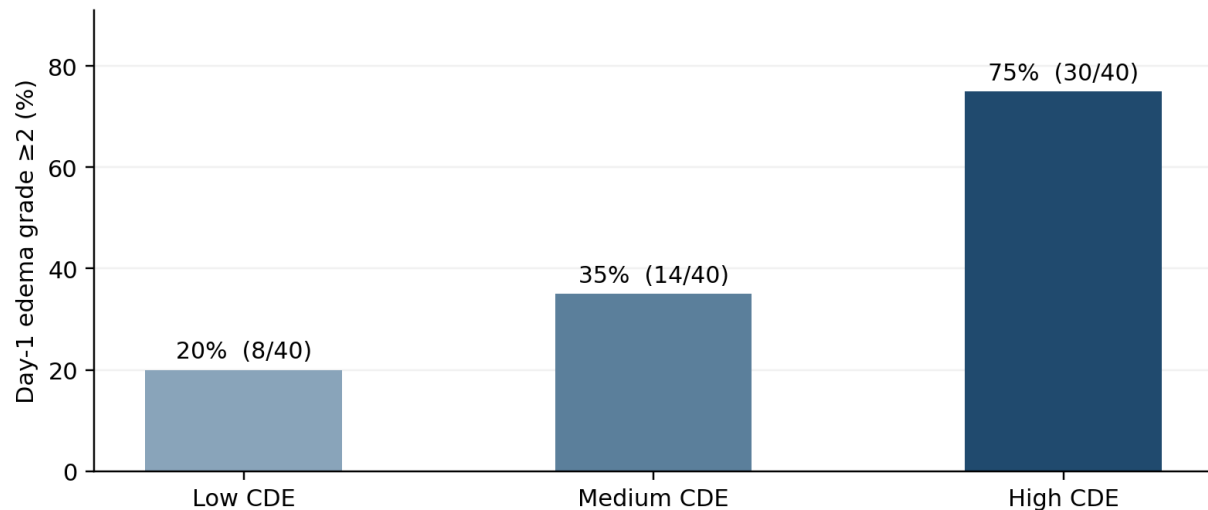


Figure 2. Frequency of clinically significant (grade ≥ 2) day-1 corneal edema by CDE tertile. The numbers above bars show percentages and events/total (40 eyes per group).

Table 2. Postoperative outcomes by CDE tertile.

Outcome	All (n = 120)	Low CDE	Medium CDE	High CDE	p
Day-1 CCT, μm	589.3 ± 37.0	572.4 ± 37.1	583.4 ± 31.0	612.2 ± 31.3	<0.001
Day-1 ΔCCT , μm	56.7 ± 25.9	38.2 ± 21.7	52.7 ± 17.9	79.2 ± 19.5	<0.001
Day-1 CCT increase, %	10.7 ± 4.9	7.1 ± 4.1	9.9 ± 3.4	14.9 ± 3.8	<0.001
Day-1 edema grade	1.3 ± 0.9	0.9 ± 0.8	1.1 ± 0.9	2.0 ± 0.8	<0.001
Edema grade ≥ 2 , n (%)	52 (43.3)	8 (20.0)	14 (35.0)	30 (75.0)	<0.001
Day-1 BCVA, logMAR	0.25 ± 0.13	0.18 ± 0.12	0.24 ± 0.11	0.34 ± 0.12	<0.001
Day-7 CCT, μm	549.3 ± 28.2	544.9 ± 29.3	546.7 ± 26.0	556.4 ± 28.5	0.150
Day-30 CCT, μm	534.2 ± 26.4	535.4 ± 28.4	531.1 ± 24.7	536.0 ± 26.3	0.668
Day-30 BCVA, logMAR	0.06 ± 0.05	0.06 ± 0.04	0.07 ± 0.05	0.07 ± 0.05	0.479
Day-30 ECD, cells/ mm^2	2270 ± 247	2365 ± 237	2271 ± 267	2174 ± 202	0.002
Day-30 ECL, %	8.4 ± 4.0	5.3 ± 3.1	8.0 ± 2.5	11.8 ± 3.3	<0.001

Table 2 note. Values are mean $\pm$ SD or n (%). The reported pairwise p values for day-1 ΔCCT after Bonferroni correction were 0.007 (low vs medium), and <0.001 (medium vs high; low vs high). ECL, percentage endothelial cell loss.

Correlations and adjusted predictors of day-1 swelling

CDE correlated with day-1 ΔCCT (Spearman $\rho = 0.71$; $p < 0.001$), day-1 edema grade ($p = 0.50$), day-1 logMAR BCVA ($p = 0.49$), day-7 residual CCT change ($p = 0.64$) and day-30 ECL ($p = 0.66$; all $p < 0.001$). CDE was not significantly correlated with day-30 BCVA ($p = 0.13$; $p = 0.144$). Day-1 ΔCCT correlated with day-30 ECL ($p = 0.51$) and day-1 BCVA ($p = 0.65$; both $p < 0.001$). Ultrasound time, aspiration time, nuclear grade and BSS volume were also correlated with ΔCCT in the reported univariable analyses.

In univariable linear regression, ΔCCT increased by $4.42 \mu\text{m}$ per 1 %-s greater CDE (95% CI 3.69–5.16; $R^2 = 0.55$). In the multivariable model, the adjusted CDE coefficient was $4.14 \mu\text{m}$ per %-s (95% CI 2.91–5.37; $p < 0.001$). Diabetes was associated with an additional $12.07 \mu\text{m}$ of swelling, and ECD with $2.90 \mu\text{m}$ less swelling per 100 cells/ mm^2 higher baseline density (Table 3). Nuclear opalescence grade and BSS volume were not significant in this CDE-adjusted model. Model R^2 was 0.694 (adjusted $R^2 = 0.672$). Reported VIFs were <4; the Shapiro–Wilk residual test gave $p = 0.21$, and HC3 robust inference did not change the CDE conclusion. Omitting nuclear grade and BSS volume gave a similar CDE coefficient ($4.17 \mu\text{m}$; 95% CI 3.54–4.79).

Table 3. Multivariable linear regression for day-1 change in central corneal thickness (μm).

Predictor	B	95% CI	Standardized effect*	p
CDE, per %-s	4.14	2.91 to 5.37	0.69	<0.001
Diabetes (yes vs no)	12.07	5.94 to 18.19	0.47*	<0.001
Preop ECD, per 100 cells/ mm^2	-2.90	-4.06 to -1.74	-0.28	<0.001
Stop-and-chop (vs divide-and-conquer)	3.63	-1.95 to 9.20	0.14*	0.200
Preop CCT, per μm	0.03	-0.07 to 0.14	0.03	0.542
Age, per year	-0.06	-0.38 to 0.25	-0.02	0.682
LOCS III NO grade, per grade	0.44	-3.50 to 4.37	0.02	0.826
BSS volume, per ml	0.01	-0.37 to 0.39	0.00	0.958

Table 3 note. $n = 120$; $R^2 = 0.694$; adjusted $R^2 = 0.672$; overall model $p < 0.001$. *The standardized-effect column is a conventional standardized coefficient for continuous covariates; for binary covariates, the source reports the between-category coefficient expressed in outcome-SD units, not a standardized beta. The unstandardized B and its 95% CI are the primary effect estimates.

Adjusted predictors and discrimination of clinically significant edema

In multivariable logistic regression, CDE remained associated with day-1 edema grade ≥ 2 (adjusted OR 1.37 per %-s; 95% CI 1.11–1.70; $p = 0.004$), as did lower baseline ECD (adjusted OR 0.79 per 100 cells/ mm^2 higher ECD; 95% CI 0.65–0.97; $p = 0.022$). Diabetes did not show a statistically significant adjusted association with this binary primary outcome (OR 1.66; 95% CI 0.64–4.32; $p = 0.300$). Nor did age, nuclear opalescence grade or BSS volume (Table 4). Reported Hosmer–Lemeshow p was 0.14; McFadden pseudo- R^2 was 0.24 and the multivariable model AUC was 0.80. The high versus low CDE tertile had a reported adjusted OR of 12.5 (95% CI 4.2–37.6), whereas the medium versus low comparison was not significant (OR 2.1; 95% CI 0.7–6.1).

Table 4. Multivariable logistic regression for clinically significant day-1 edema (grade ≥ 2).

Predictor	Adjusted OR	95% CI	p
CDE, per %-s	1.37	1.11–1.70	0.004
Preop ECD, per 100 cells/ mm^2	0.79	0.65–0.97	0.022
Diabetes (yes vs no)	1.66	0.64–4.32	0.300
LOCS III NO grade, per grade	0.96	0.52–1.78	0.905
BSS volume, per ml	0.99	0.94–1.05	0.783
Age, per year	1.00	0.95–1.05	0.923

Table 4 note. $n = 120$; 52 primary-outcome events. ORs are adjusted for all covariates in the table. Likelihood-ratio model $p < 0.001$. The apparent AUC of CDE alone for grade ≥ 2 edema was 0.78 (reported 95% bootstrap CI 0.69–0.86). The study-sample Youden threshold of 8.4 %-s identified 37 true positives, 18 false positives, 15 false negatives and 50 true negatives. These counts imply sensitivity 37/52 = 71.2%, specificity 50/68 = 73.5%, positive predictive value 37/55 = 67.3% and negative predictive value 50/65 = 76.9%. Total ultrasound time had the same reported AUC (0.78). These are apparent estimates derived from the same dataset used to select the CDE threshold.

Endothelial cell loss and visual recovery

Mean day-30 ECL was $8.4 \pm 4.0\%$, increasing from $5.3 \pm 3.1\%$ (low tertile) to $8.0 \pm 2.5\%$ (medium) and $11.8 \pm 3.3\%$ (high; $p < 0.001$; Figure 3). In the reported multivariable model adjusted for age, diabetes, baseline ECD and surgical technique, each 1 %-s higher CDE was associated with 0.58 percentage points greater ECL (95% CI 0.46–0.69; $p < 0.001$). Diabetes was associated with approximately 2.0 percentage points greater ECL, whereas stop-and-chop was associated with 1.8 points less ECL than divide-and-conquer, conditional on the model covariates. Mean BCVA improved from 0.49 ± 0.18 logMAR preoperatively to 0.06 ± 0.05 at day 30 ($p < 0.001$); 94/120 eyes (78.3%) achieved 0.1 logMAR or better. Day-30 BCVA did not differ significantly between CDE tertiles ($p = 0.479$).

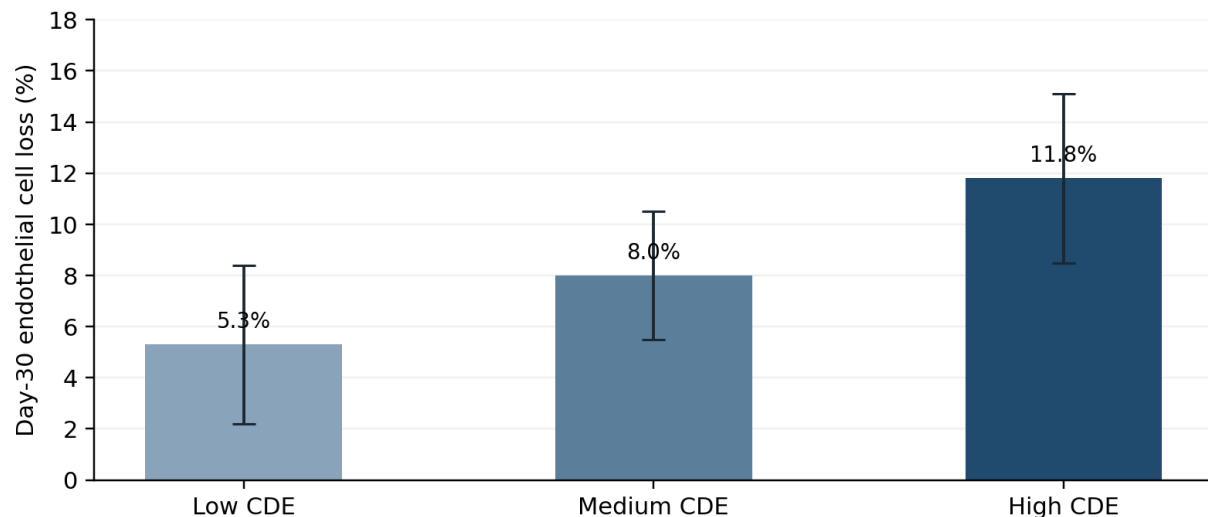


Figure 3. Mean $\pm$ SD endothelial cell loss at day 30 by CDE tertile (n = 40 per group). Error bars represent the reported within-group standard deviations, not confidence intervals.

DISCUSSION

In this prospective single-surgeon cohort, higher intraoperative CDE was associated with greater day-1 corneal thickening, a higher prevalence of clinically significant slit-lamp edema and greater ECL at one month. The association remained after adjustment for major baseline characteristics and operative variables. In contrast, average CCT returned close to its preoperative level by day 30, and visual acuity at that point was similar among CDE tertiles. These findings characterize early corneal vulnerability rather than persistent postoperative visual impairment.

The associations are biologically plausible: greater ultrasound exposure may coincide with more cavitation, temperature change, turbulence and mechanical contact that stress the endothelial pump and barrier (2–4). The day-1 Δ CCT correlation with day-30 ECL is consistent with Lundberg and colleagues' observation that early postoperative swelling relates to subsequent endothelial loss (10). Nevertheless, CCT thickening is not a direct measurement of endothelial injury, and postoperative inflammatory or fluidic factors may also contribute (2).

Recent comparative investigations provide context. Vasavada et al. reported that a lower-CDE femtosecond-assisted group had less early CCT thickening and clearer corneas than conventional phacoemulsification in junior-surgeon cases (6). Ganesh et al. similarly found greater day-1 corneal edema and six-month ECD loss with conventional surgery than femtosecond-assisted surgery in dense cataracts (14). In a randomized comparison of nuclear-disassembly methods, Tao et al. reported less CDE and milder early corneal edema with reverse chopper-assisted prechop than phaco-chop, although one-month ECL did not differ significantly (13). These studies support an association between surgical energy use and postoperative corneal effects, but their comparisons differ from the present observational contrast across naturally occurring CDE values.

Nuclear grade was strongly associated with CDE in the present sample ($p = 0.83$). Its nonsignificance in CDE-adjusted models is compatible with shared information between the variables, but it does not establish that CDE mediates the effect of cataract density or removes all independent effects of nuclear hardness. Likewise, BSS volume is correlated with the course and complexity of surgery, and its regression coefficient does not isolate fluid-induced injury. Bui et al. identified cataract grade, surgical technique, age and operator-related characteristics as determinants of CDE, emphasizing that it can act as a composite marker of surgical difficulty (9).

Lower preoperative ECD was associated with both continuous swelling and the binary edema outcome. Diabetes was associated with greater Δ CCT and ECL, but was not independently associated with grade ≥ 2 edema in the reported logistic model. This distinction is important: a significant association with one outcome definition does not imply significance with another. A 2023 meta-analysis found greater postoperative endothelial vulnerability in patients with diabetes than in those without diabetes, broadly supporting the continuous-outcome pattern while also highlighting differences in study populations and follow-up schedules (7).

The 8.4 %-s Youden threshold offered moderate in-sample discrimination, but its sensitivity, specificity and predictive values were measured in the development cohort. As total ultrasound time yielded an identical AUC, CDE did not demonstrate superiority to this simpler parameter on the reported discrimination metric. Model calibration and the clinical value of a CDE-based rule require more extensive study, including optimism correction, external validation and comparison with baseline risk markers. Device choice also matters: Ricks et al. found that reported CDE and directly measured phaco-tip energy could diverge between longitudinal and torsional modalities (11). Therefore, a threshold derived on one platform should not be assumed portable to another.

The reduction in mean CCT swelling by day 30 suggests that much of the early effect was transient, but day-30 ECL increased with CDE. This separation between temporary pachymetric thickening and persisting cell-density reduction warrants longer follow-up. The association of surgical technique with ECL after adjustment should also be interpreted cautiously because technique was selected by the surgeon, not randomized. The results support routinely considering CDE alongside endothelial reserve during postoperative risk assessment, but they do not establish that changing medication intensity or follow-up frequency based on this cut-off improves patient outcomes.

STRENGTHS AND LIMITATIONS

Strengths include a prospective design, one eye per patient, consistent surgical operator and protocol, masked day-1 edema assessment, objective serial pachymetry, day-30 specular microscopy and multivariable adjustment for nuclear grade and baseline ECD. The cohort also considered clinical edema as a binary outcome as well as CCT change as a continuous measurement.

Limitations include the single-center, single-surgeon setting and restriction to uncomplicated surgery using one longitudinal phacoemulsification approach, which reduce external generalizability. Selection of nucleus-disassembly technique by the surgeon may confound technique comparisons. Correlation among CDE, nuclear density, ultrasound time and fluidic parameters complicates causal interpretation. With 52 events in a six-predictor logistic model, some coefficient estimates may be unstable, particularly in subgroups; the width of certain confidence intervals reflects this uncertainty. Clinical edema grading is partly subjective despite masking, and postoperative edema grades were defined at day 1 rather than tracked across all visits. The CDE cut-off was optimized and evaluated in the same cohort, without optimism-corrected or external validation. Follow-up ended at day 30, precluding conclusions about longer-term endothelial trajectories. Exclusion of eyes with low ECD, corneal disease or complicated surgery further restricts applicability to higher-risk patients.

Further prospective multicenter work should test model transportability and threshold stability across surgeons and phacoemulsification systems, assess incremental value over established preoperative parameters, and determine whether risk-guided postoperative review improves outcomes.

CONCLUSION

Higher cumulative dissipated energy was associated with greater day-1 corneal edema and CCT increase after uncomplicated phacoemulsification, independently of the covariates examined. Greater CDE was also associated with endothelial cell loss at day 30, although mean corneal thickness returned close to baseline. CDE may be a useful complementary marker of early postoperative corneal risk, but the proposed threshold requires further validation before clinical implementation.

REFERENCES

1. Sharma N, Singhal D, Nair SP, Sahay P, Sreeshankar SS, Maharana PK. Corneal edema after phacoemulsification. *Indian J Ophthalmol.* 2017;65(12):1381–1389.
2. Briceno-Lopez C, Burguera-Giménez N, García-Domene MC, Díez-Ajenjo MA, Peris-Martínez C, Luque MJ. Corneal edema after cataract surgery. *J Clin Med.* 2023;12(21):6751. doi:10.3390/jcm12216751.
3. Walkow T, Anders N, Klebe S. Endothelial cell loss after phacoemulsification: relation to preoperative and intraoperative parameters. *J Cataract Refract Surg.* 2000;26(5):727–732.
4. Hayashi K, Hayashi H, Nakao F, Hayashi F. Risk factors for corneal endothelial injury during phacoemulsification. *J Cataract Refract Surg.* 1996;22(8):1079–1084.
5. Storr-Paulsen A, Norregaard JC, Ahmed S, Storr-Paulsen T, Pedersen TH. Endothelial cell damage after cataract surgery: divide-and-conquer versus phaco-chop technique. *J Cataract Refract Surg.* 2008;34(6):996–1000.
6. Vasavada AR, Vasavada SA, Nath V, Vasavada V, Patel P. FLACS vs conventional phacoemulsification by junior cataract surgeons: randomized trial. *J Cataract Refract Surg.* 2023;49(2):159–164. doi:10.1097/j.jcrs.0000000000001061.
7. Yang Y, Chai H, Ding Z, Tang C, Liang Y, Li Y, et al. Meta-analysis of corneal endothelial changes after phacoemulsification in diabetic and non-diabetic patients. *BMC Ophthalmol.* 2023;23:174. doi:10.1186/s12886-023-02924-2.
8. Lee JS, Lee JE, Choi HY, Oum BS, Cho BM. Corneal endothelial cell change after phacoemulsification relative to the severity of diabetic retinopathy. *J Cataract Refract Surg.* 2005;31(4):742–749.
9. Bui AD, Sun Z, Wang Y, Huang S, Ryan M, Yu Y, et al. Factors impacting cumulative dissipated energy levels and postoperative visual acuity outcome in cataract surgery. *BMC Ophthalmol.* 2021;21:439. doi:10.1186/s12886-021-02205-w.
10. Lundberg B, Jonsson M, Behndig A. Postoperative corneal swelling correlates strongly to corneal endothelial cell loss after phacoemulsification cataract surgery. *Am J Ophthalmol.* 2005;139(6):1035–1041.
11. Ricks RG, Cardenas IA, Jensen JL, Nelson TK, Olson RJ, Pettey JH. Discrepancies in CDE and measured phaco tip energy: comparison of energy produced in longitudinal and torsional ultrasound using calorimetry. *Med Devices (Auckl).* 2024;17:339–348. doi:10.2147/MDER.S484843.
12. Chen M, Anderson E, Hill G, Chen JJ, Patianakos T. Comparison of cumulative dissipated energy between the Infiniti and Centurion phacoemulsification systems. *Clin Ophthalmol.* 2015;9:1367–1372.
13. Tao J, Wan Y, Song X. Comparison of the reverse chopper-assisted prechop and phaco-chop nucleotomy techniques during phacoemulsification for cataracts with grade III nuclei: a randomized controlled trial. *Ann Transl Med.* 2023;11(2):105. doi:10.21037/atm-22-6163.
14. Ganesh S, Brar S, Wadhokar S. Changes in endothelial cell density after conventional phacoemulsification and FLACS in eyes with dense cataracts. *J Cataract Refract Surg.* 2024;50(6):572–577. doi:10.1097/j.jcrs.0000000000001408.
15. Chylack LT Jr, Wolfe JK, Singer DM, et al. The Lens Opacities Classification System III. *Arch Ophthalmol.* 1993;111(6):831–836.