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Artificial Intelligence Assisted Cataract Surgery: A Comparative Clinical Evaluation of Conventional and AI-Assisted Surgical Approaches

Ali Tonuzi[1], Orjeta Tonuzi[1], Migena Beqiri[2], Luan Qafmolla[3]*

[1]University Hospital Center "Mother Theresa", Tirana, Albania
[2]Albanian Eye Center, Tirana, Albania
[3]Faculty of Natural Science, Tirana, Albania
Email: *luan.qafmolla@fshn.edu.al

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Abstract

Artificial intelligence (AI) has emerged as an important innovation in ophthalmology, providing new opportunities to improve the diagnosis, surgical planning, and management of cataract. AI-assisted technologies have demonstrated considerable potential to enhance surgical precision, optimize intraoperative decision-making, and improve postoperative outcomes. However, evidence supporting their routine clinical application remains limited. This study aimed to evaluate the impact of AI-assisted technologies on diagnostic accuracy, surgical precision, intraoperative performance, and postoperative clinical outcomes compared with conventional cataract surgery. A combined retrospective and prospective comparative clinical study was conducted involving 98 patients who underwent cataract surgery between **May 2019** and **April 2026**. Patients were allocated into two groups according to the surgical approach employed: ***Group A*** (conventional cataract surgery, n = 55) and ***Group B*** (AI-assisted cataract surgery, n = 43). Clinical outcomes were assessed by comparing preoperative and postoperative evaluations performed at the final follow-up visit. The primary endpoint was postoperative visual acuity (VA), while secondary endpoints included refractive accuracy, intraocular pressure (IOP), intraoperative performance, surgical precision, and postoperative complication rates. Continuous variables were analyzed using appropriate parametric or non-parametric statistical tests according to data distribution, and categorical variables were compared using Chi-square or Fisher's exact test, with statistical significance established at $P < 0.05$. Compared with *Group A* surgery, the *Group B* approach achieved significantly better postoperative visual acuity (0.51 ± 0.13 vs. 0.42 ± 0.15 decimal units, P < 0.001). Achievement of the target postoperative refraction (±0.5 D) was significantly higher in the *Group B* than in the *Group A* (87% vs. 71%, $P = 0.03$), indicating improved accuracy of AI-assisted intraocular lens (IOL) power calculation. Mild postoperative complications, including transient corneal edema and temporary intraocular pressure elevation, occurred in 19% of patients in the *Group B* and 23% in the *Group A*, with no statistically significant difference between groups (**P = 0.64**). AI-assisted cataract surgery represents a valuable advancement in contemporary ophthalmic practice by improving refractive predictability, surgical precision, and perioperative clinical decision-making. Nevertheless, AI should be considered a complementary clinical tool that supports, rather than replaces, the expertise and clinical judgment of experienced ophthalmic surgeons. Further prospective multicenter studies with larger patient populations are warranted to confirm its long-term clinical effectiveness, safety, and cost-effectiveness.

Keywords

Artificial Intelligence, Cataract Surgery, Phacoemulsification, Intraocular Lens, Optical Coherence Tomography, Refractive Accuracy, Ophthalmology

1. Introduction

Artificial Intelligence (AI) has emerged as one of the most transformative technological developments in contemporary medicine, substantially improving diagnostic accuracy, clinical decision-making, and surgical performance across multiple medical disciplines [1] (***applications of AI in cataract surgery; a review***) Within ophthalmology, AI-based technologies have demonstrated considerable clinical applicability owing to the image-intensive nature of ocular diagnostics. and the widespread integration of digital imaging platforms into routine clinical practice [1] [2] (***AI applications and cataract management***). Cataract surgery, currently the most frequently performed ophthalmic surgical procedure worldwide, has become a major field for the implementation of AI-assisted systems designed to optimize perioperative assessment, surgical precision, and postoperative patient management.

Recent advances in machine learning (ML), deep learning (DL), computer vision algorithms, and AI-assisted imaging technologies have significantly enhanced automated ocular image analysis, biometric prediction, intraocular lens (IOL) power calculation, and intraoperative guidance. Modern ophthalmic platforms integrating optical coherence tomography (OCT), AI-assisted biometric devices, and image-recognition systems have demonstrated considerable potential to improve refractive predictability while reducing variability in surgical planning and execution [3] **(*Application of AI for automatic cataract… images: comparing automatic… segmentation*).** Furthermore, AI-driven analytical models have shown demonstrated utility in identifying patients at increased risk of postoperative complications and supporting individualized surgical planning.

Although the scientific literature published over the past decade has documented substantial technological progress in AI-assisted ophthalmology, important limitations remain regarding the translation of these innovations into routine clinical practice. Most published investigations have primarily focused on algorithm development, computational performance, and image-classification accuracy, whereas comparatively fewer studies have directly compared AI-assisted and conventional cataract surgery under real-world clinical conditions. Moreover, many studies are limited by relatively small sample sizes, short follow-up periods, insufficient external validation, and heterogeneity in study design and clinical implementation. Consequently, the clinical effectiveness, reproducibility, and practical applicability of AI-assisted cataract surgery continue to require further evidence-based evaluation [3].

Another important consideration involves the relationship between AI-supported technologies and surgeon-dependent expertise. Despite the growing sophistication of intelligent computational systems, successful ophthalmic surgery continues to rely heavily on clinical judgment, intraoperative adaptability, and the experience of the operating surgeon, particularly in anatomically complex or high-risk cases. Therefore, current scientific perspectives increasingly support the concept of a hybrid clinical model in which AI technologies function as complementary decision-support tools rather than replacements for physician expertise.

The present study was designed to address several of these existing research gaps by providing a retrospective-prospective comparative evaluation of AI-assisted versus conventional cataract surgery in a real-world tertiary ophthalmic care setting. Specifically, this investigation aimed to assess differences in visual acuity outcomes, refractive precision, intraoperative stability, complication rates, and procedural standardization between the two surgical approaches. In addition, the study evaluates the practical feasibility and clinical challenges associated with implementing AI-assisted technologies within routine ophthalmic surgical practice. Through this approach, the study seeks to provide clinically relevant evidence regarding the role of AI integration in improving surgical outcomes and optimizing contemporary cataract management strategies [4] (***AI in cataract surgery*: *Smart screening*, *precision planning*, *and cataract coaching***).

1.1. Evolution of Artificial Intelligence in Cataract Surgery

The evolution of artificial intelligence (AI) in ophthalmology, particularly in cataract and refractive surgery, has progressed through several distinct yet interrelated phases, reflecting continuous advances in computational capacity, data availability, imaging technologies, and clinical integration. Over the past decade, with substantial contributions from European and international research communities, AI has evolved from relatively simple rule-based decision-support systems into sophisticated data-driven clinical platforms capable of supporting diagnosis, surgical planning, intraoperative guidance, and postoperative outcome prediction. Based on the current literature, the development of AI in cataract surgery can be broadly categorized into four major phases, as summarized in **Table 1**.

Table 1. Progressive evolution of AI in cataract and refractive surgery.

Period	Major technological milestones
Pre-2015	Early developments were characterized by rule-based formulas and basic imaging technologies. Initial computer-assisted diagnostic systems emerged during the 1980s, primarily for automated retinal disease screening, establishing the foundation for subsequent integration of computational methods into ophthalmology.
2015-2020	The introduction of machine learning (ML) represented a major technological milestone by enabling structured analysis of ophthalmic imaging data. This period culminated in the widespread adoption of deep learning (DL), particularly convolutional neural networks (CNNs), which substantially improved automated image interpretation, disease classification, and diagnostic accuracy using large-scale ophthalmic datasets.
2020-2023	AI applications expanded considerably into cataract care. Major developments included: 1) automated cataract detection and grading; 2) enhanced intraocular lens (IOL) power calculation; and 3) predictive models supporting surgical planning and perioperative risk stratification. During this period, European ophthalmology also experienced increasing adoption of advanced surgical technologies, including femtosecond laser-assisted cataract surgery, thereby establishing the technological infrastructure required for AI-integrated clinical workflows [4].
2023-2026	Contemporary AI systems increasingly support intraoperative and postoperative clinical decision-making through real-time prediction of surgical complications, objective assessment of surgical performance, and prediction of postoperative in routine clinical practice. This period has been characterized by growing emphasis on personalized medicine, workflow efficiency, robust clinical validation, and interoperability between diagnostic and therapeutic platforms. Furthermore, professional organizations, particularly the European Society of Cataract and Refractive Surgeons (ESCRS), have played a central role in promoting clinical research, multicenter validation studies, educational initiatives, and ethical frameworks supporting the responsible implementation of AI in ophthalmology

Abbreviations: AI, Artificial Intelligence; ML, Machine Learning; DL, Deep Learning; CNNs, Convolutional Neural Networks; IOL, Intraocular Lens; ESCRS, European Society of Cataract and Refractive Surgeons.

Current the European literature highlights a clear transition toward patient-centered digital ecosystems, characterized by: **1)** AI-assisted surgical planning platforms; **2)** integration of AI into routine clinical workflows; and **3)** enhanced interoperability between diagnostic and therapeutic systems. Despite these technological advancements, current evidence consistently underscores that optimal

AI performance in cataract surgery is contingent upon three fundamental pillars: **a)** intelligent screening systems enabling early and accurate detection; **b)** precise and efficient AI driven tools for surgical planning and execution; and **c)** highly trained ophthalmic professionals responsible for interpreting outputs and ensuring safe, ethical, and patient-centered care. In this context, the evolution of AI in cataract surgery reflects not only rapid technological innovation but also the continuing need to harmonize advanced computational systems with human clinical expertise [4] [5] (***Accuracy and safety of an autonomous AI clinical assistant conducting telemedicine follow-up assessment for cataract surgery***).

1.2. AI in Ocular Biometry and Surgery

Artificial intelligence has become increasingly integrated into modern ocular biometry and cataract surgery by supporting multiple stages of the clinical workflow, including preoperative evaluation, biometric analysis, IOL power calculation, surgical planning, intraoperative guidance, and postoperative assessment. The integration of AI-driven technologies has substantially improved the accuracy, reproducibility, and efficiency of clinical decision-making while facilitating a more personalized approach to cataract management [6] and [7] (***Comparison of… guided… for planning precise… IOL calculation and…***) and [7] (***Applications of AI in cataract surgery***).

One of the most important applications of AI is the optimization of ocular biometric analysis. Accurate measurement of axial length, corneal curvature, anterior chamber depth, lens thickness, and other biometric parameters is essential for precise IOL power calculation and successful refractive outcomes. AI-based algorithms are capable of integrating large volumes of biometric information obtained from OCT, optical biometers, corneal topography, tomography, and anterior-segment imaging systems to generate increasingly accurate predictive models for postoperative refractive outcomes [8] (***AI in cornea, refractive surgery…and future directions***).

Recent AI-assisted IOL calculation formulas have demonstrated superior predictive performance compared with several conventional theoretical and regression-based formulas, particularly in eyes presenting with atypical biometric characteristics or previous corneal refractive surgery. By simultaneously analyzing multiple biometric variables and continuously learning from expanding clinical datasets, AI algorithms can improve refractive predictability while reducing postoperative refractive error [9] (***AI in ophthalmology: Improved diagnostic precision***).

Beyond biometric prediction, AI has substantially expanded its role in preoperative risk stratification and surgical planning. ML models are increasingly capable of identifying patients at elevated risk for intraoperative complications, estimating surgical complexity, and supporting individualized selection of surgical techniques based on patient-specific anatomical and clinical characteristics. These predictive capabilities enable surgeons to optimize perioperative planning and improve procedural safety before entering the operating room [10] (***AI manages congenital cataract…and telehealth computing***).

During surgery, AI-assisted image analysis and computer-assisted guidance systems provide real-time support by improving tissue recognition, optimizing surgical alignment, monitoring instrument positioning, and facilitating standardization of critical surgical steps. These technologies contribute to greater procedural consistency, enhanced surgical precision, and reduced operator-dependent variability while preserving full surgeon control throughout the procedure [11] (***Effectiveness of AI as a support tool…. for cataract surgery, a step … patient management***).

Postoperatively, AI applications extend to automated monitoring of visual recovery, refractive stability, intraocular pressure, and early detection of postoperative complications through integration of multimodal imaging and electronic clinical records. Continuous analysis of postoperative data further enables AI systems to refine predictive models, thereby supporting ongoing improvements in clinical performance and personalized patient management [12] (***Application of AI for automatic cataract staging based…segment images, comparing automatic segmentation approaches to manual segmentation***).

Despite these remarkable technological advances, several important challenges continue to limit the widespread implementation of AI in routine cataract surgery. Current AI systems remain highly dependent on the quality, diversity, and representativeness of training datasets, external validation across different populations, algorithm transparency, cybersecurity, regulatory approval, and interoperability with existing clinical infrastructures. Ethical considerations, including patient privacy, data governance, algorithmic bias, and physician accountability, also require continuous attention as AI becomes increasingly integrated into clinical practice. [13] (***Application of AI in the analysis of features affecting cataract surgery complication…***).

Consequently, the current body of evidence supports a collaborative model of cataract surgery in which artificial intelligence serves as an advanced clinical decision-support tool rather than an autonomous surgical system. AI has the potential to enhance diagnostic accuracy, optimize surgical planning, improve refractive predictability, and support intraoperative decision-making; however, successful clinical implementation continues to depend on the expertise, judgment, and experience of ophthalmic surgeons. The greatest clinical benefit is therefore expected from a hybrid approach that combines computational intelligence with human clinical expertise, ensuring safe, effective, and patient-centered cataract care [6] [13].

1.3. Study Objective

This study combined retrospective and prospective analyses conducted at the tertiary ophthalmology center, Albanian Eye Center (AEC), between May 2019 and April 2026.

The primary objective of this study was to comparatively evaluate the clinical performance of conventional and artificial intelligence (AI)-assisted cataract surgery in patients undergoing phacoemulsification for age-related cataract. Specifically, the study aimed to determine whether the integration of AI-assisted technologies improves postoperative visual acuity, refractive accuracy, surgical precision, intraoperative performance, and overall clinical outcomes compared with conventional cataract surgery.

Secondary objectives included the assessment of postoperative intraocular pressure, perioperative complication rates, surgical workflow standardization, and the contribution of AI-assisted diagnostic imaging, biometric analysis, and intraocular lens power calculation to clinical-decision making and surgical planning. In addition, the study evaluated the practical applicability, potential limitations, and future role of AI-assisted technologies as complementary decision-support tools in routine ophthalmic practice.

By comparing conventional and AI-assisted surgical approaches in a real-world clinical setting, this study seeks to provide evidence regarding the effectiveness, safety, and clinical value of the integration of AI in cataract surgery, while supporting the development of evidence-based strategies for optimizing patient outcomes and advancing modern ophthalmic surgical practice.

2. Material and Methods

This combined retrospective and prospective comparative clinical study was designed to evaluate the clinical performance of conventional and artificial intelligence (AI)-assisted cataract surgery in patients undergoing phacoemulsification for age-related cataract. The study compared diagnostic assessment, surgical planning, intraoperative performance, postoperative visual and refractive outcomes, and perioperative complications between conventional and AI-assisted surgical approaches. Patient selection, clinical evaluation, surgical procedures, outcome assessment, and statistical analysis were performed using standardized institutional protocols to ensure methodological consistency and reproducibility. This investigation was designed and reported in accordance with the ***S***trengthening the ***R***eporting of ***O***bservational ***S***tudies in ***E***pidemiology (STROBE) recommendations for comparative observational clinical studies.

2.1. Data Collection and Study Population

A total of 98 patients diagnosed with age-related cataract and undergoing primary cataract surgery between May 2019 and April 2026 were included in this combined retrospective and prospective comparative clinical study. Clinical data were retrieved from the institutional electronic medical records and the cataract surgery registry maintained at the AEC facility, in accordance with the center's standardized clinical protocol for corneal, refractive, and cataract surgery [14] (***Steps of protocol to scenario of cornea, refractive surgery, and cataract in facility "AEC"***).

Patients were allocated to the study groups according to the period during which surgery was performed and the availability of AI-assisted technologies in routine clinical practice. No randomization was performed.

Group A (conventional approach) consisted of 55 patients who underwent standard cataract surgery between May 2019 and April 2023, without the use of artificial intelligence (AI)-assisted technologies. ***Group B*** (AI-assisted approach) included 43 patients who underwent cataract surgery between October 2023 and April 2026, during which AI-integrated technologies were incorporated into the diagnostic and surgical workflow.

The study population comprised 55 females (56.1%) and 43 males (43.9%). Most participants (65.3%, n = 64) resided in rural areas, whereas 34.7% (n = 34) were from urban regions of Albania and Kosovo, reflecting the geographical distribution of patients attending the study center.

Participants ranged in age from 45 to 80 years and were categorized into three predefined age groups (45 - 69, 70 - 75, and 76 - 80 years). As shown in Table below, the largest proportion of patients (49.0%, n = 48) belonged to the 45 - 69-year age group, followed by 35.7% (n = 35) in the 70 - 75-year group and 15.3% (n = 15) in the 76 - 80-year group. The age and sex distribution of the study population is summarized in Table 2 [15] (***Prevalence and risk factors for age-related cataract in Sweden***).

All demographic and baseline clinical data were collected before surgery using standardized case report forms and institutional ophthalmic assessment protocols.

Clinical information was collected using standardized ophthalmic assessment procedures, including comprehensive ophthalmic examination, slit-lamp biomicroscope, ocular imaging, and structured patient questionnaires.

Table 2. Distribution of study participants according to age group and sex.

Age group (years)	Female n (%)	Male n (%)	Total n (%)
45 - 69	28 (50.9)	20 (46.5)	48 (49.0)
70 - 75	18 (32.7)	17 (39.5)	35 (35.7)
76 - 80	9 (16.4)	6 (14.0)	15 (15.3)
Total	**55 (100)**	**43 (100)**	**98 (100)**

2.2. Clinical and Imaging Data Acquisition

The study incorporated both clinical examination findings and questionnaire-based information. A structured questionnaire was administered during the preoperative evaluation to collect detailed medical, ophthalmic, and family histories, enabling assessment of potential risk factors associated with cataract development using standardized institutional data collection procedures [14], which was completed during the preoperative evaluation using standardized institutional data collection procedures.

Analysis of these data indicated a strong association between cataract prevalence and increasing age, particularly in individuals aged 70 - 75 years, irrespective of gender.

Anterior segment images were acquired using digital slit-lamp biomicroscopy under standardized imaging protocols. All images were captured by experienced ophthalmic technologists to ensure consistency and reproducibility. Image acquisition was performed using the same institutional imaging protocol for all study participants to minimize inter-examination variability.

Inclusion criteria required high-quality digital images that clearly demonstrated cataract characteristics across different stages of lens opacity. Images with poor resolution, motion artifacts, or significant interference from corneal pathology were excluded from the analysis. Only images considered of sufficient quality for clinical interpretation and AI-assisted image analysis were included in the study.

2.3. Patient Selection and Eligibility Criteria

Patient selection was performed according to predefined eligibility criteria to ensure cohort homogeneity and facilitate a reliable comparison between the conventional and AI-assisted cataract surgery workflows. Eligible participants were consecutive outpatients diagnosed with age-related cataract, who underwent routine phacoemulsification at the "Albanian Eye Center" during the study period. The patient selection process, eligibility criteria, reasons for exclusion, and surgical standardization are summarized in Table 3 and in workflow diagram Figure 1.

Table 3. Patient selection, eligibility criteria, surgical standardization & AI-assisted clinical workflow.

Category	Variable	Description/Value
Study population	Study design, period & center	**Combined retrospective-prospective comparative clinical study, May 2019-April 2026, "Albanian Eye Center"**
	Patients screened	**260**
	Patients excluded	**162**
	Patients included	**98**
	Group A	Conventional workflow (**n = 55**)
	Group B	AI-assisted workflow (**n = 43**)
	Unit of analysis	☐ One eye per patient ☐ Both eyes
Eligibility criteria	**Inclusion criteria**	Age-related cataract; elective phacoemulsification; complete ophthalmic examination; complete biometric assessment; available clinical records; eligibility for routine cataract surgery
	Exclusion criteria	Previous intraocular surgery; retinal or macular pathology; severe zonular instability; corneal opacity; chronic ocular inflammation; anterior segment abnormalities; incomplete records
Reasons for exclusion	Previous intraocular surgery	**n = 30** (Patients with previous intraocular surgery, because prior surgery may alter ocular anatomy, increase the risk of complications, affect wound healing, and confound the assessment of treatment outcomes)

Continued

	Retinal/macular pathology	**n = 32** (Patients with retinal or macular pathology, because these conditions may independently impair visual acuity, limit visual recovery after surgery, and confound the assessment of postoperative outcomes)
	Zonular instability	n = (18) Patients with zonular instability, because weakened zonular support increases the risk of intraoperative and postoperative complications, requiring modified surgical techniques or additional devices etc.
	Corneal opacity	n = (22) Patients with corneal opacity, because may impair intraoperative visualization, independently reduce visual acuity, interfere with accurate biometric measurements, and confound postoperative outcomes
	Incomplete clinical records	n = 40 Patients with incomplete clinical records, because missing preoperative or postoperative data precluded accurate assessment of surgical outcomes and could introduce bias into the analysis.
	Other	n = 20 Patients with systemic conditions that could increase surgical risk or interfere with the accurate assessment of postoperative outcomes
Surgical standardization	Number of surgeons	3 (one specialist and 2 assistants)
	Surgeon experience	>20 years the specialist; assistants 2 - 3 years
	Comparable experience	**Yes**/No
	Surgical technique	Standard phacoemulsification
AI-assisted workflow	Imaging platform	Pentacam HR
	AI platform	Alcon SMART Cataract
	AI functions	Automated image analysis, biometric integration, digital surgical planning
	Final clinical decision	Attending ophthalmologist

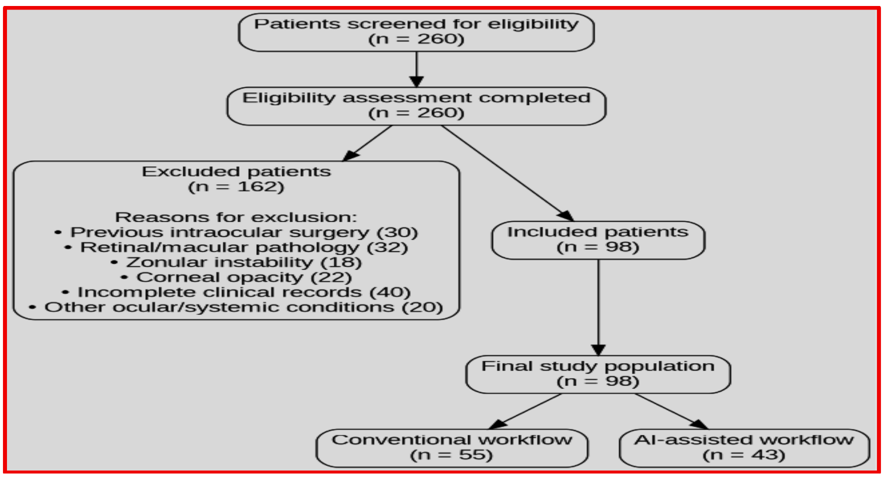

Figure 1. Patient selection flow diagram.

Patients with ocular conditions that could substantially influence surgical complexity or postoperative visual outcomes were excluded from the analysis. These included previous intraocular surgery, clinically significant retinal or macular disease, severe zonular instability, chronic ocular inflammatory disorders, corneal opacities compromising imaging quality, and other major anterior segment abnormalities. Patients with incomplete clinical documentation or insufficient follow-up were also excluded.

The predefined eligibility criteria were established before patient enrollment and were applied uniformly throughout the study period to minimize potential confounding factors and ensure comparability between the conventional and AI-assisted clinical workflows [16] (***The impact of AI in general surgery, enhancing precision, efficiency and outcomes***).

Artificial intelligence was implemented exclusively as a clinical decision-support tool, and no additional eligibility criteria were introduced specifically for AI-assisted evaluation [7] [14] [17] (***Evolution and applications of AI to cataract surgery***).

2.4. Methodology of Conventional Phacoemulsification Cataract Surgery

Phacoemulsification remains the gold standard surgical technique for cataract extraction. Its primary objective is the restoration of visual function through removal of the opacified crystalline lens, followed by implantation of an IOL. In the present study, the conventional surgical technique was performed according to the standardized institutional cataract surgery protocol. The sequential surgical steps are illustrated using representative intraoperative photographs obtained during conventional phacoemulsification surgery.

1) ***Preoperative preparation and anesthesia***, In accordance with the institutional surgical protocol, the procedure begins with sterile preparation of the operative field. The periocular skin is disinfected, and sterile drapes are applied. An eyelid speculum is inserted to ensure adequate surgical exposure. Local anesthesia was administered either topically (eye drops) or by periocular injection, depending on patient characteristics and surgical complexity (**Figure 2**: photo 1).

2) ***Creation of the corneal incision***, a self-sealing clear corneal incision of approximately 2-3 mm is created using a keratome, typically at the limbus or within the clear cornea. A secondary side port incision may be made to facilitate instrument access. This micro-incision is essential for maintaining anterior chamber stability, minimizing surgically induced astigmatism, and enabling sutureless wound closure (**Figure 2**: photo 2).

3) ***Continuous curvilinear capsulorhexis***, a circular opening is created in the anterior lens capsule using capsulorhexis forceps. The goal is to achieve a well-centered, continuous circular capsulotomy (approximately 5.0 mm in diameter), ensuring capsular integrity for optimal IOL centration, long-term stability, and favorable postoperative refractive outcomes (**Figure 2**: photo 3).

4) The procedure continues with hydrodissection to separate the cortical material from the lens capsule, followed by hydrodelineation to separate the nucleus from the epinucleus. These maneuvers facilitate free rotation of the nucleus while reducing stress on the zonular fibers, thereby improving the safety and efficiency of the subsequent phacoemulsification procedure.

5) ***Phacoemulsification*** **(*****ultrasonic fragmentation*****),** an ultrasonic phacoemulsification probe is introduced through the main corneal incision to fragment the lens nucleus. The fragmented nucleus is simultaneously emulsified and aspirated, thereby minimizing intraocular manipulation and reducing potential trauma to the corneal endothelium and surrounding intraocular structures (Figure 2: photo 4).

6) After cortical cleanup (irrigation/aspiration), a foldable (IOL) was inserted through the small corneal incision using an injector system. The IOL was positioned within the capsular bag to ensure proper centration, long-term stability, and an optimal refractive outcome (Figure 2: photo 5).

7) ***Final step and wound closure*****,** the corneal incision is hydrated (stromal hydration) to promote self-sealing, typically without the need for sutures. Final intraoperative assessment included verification of anterior chamber stability, correct IOL positioning, and the absence of wound leakage. The integrity of the surgical wound was confirmed before completion of the procedure. Intracameral antibiotics may be administered to reduce the risk of postoperative endophthalmitis [14]. The conventional phacoemulsification technique described above served as the reference surgical procedure for comparison with the AI-assisted surgical approach. All procedures were performed by experienced ophthalmic surgeons following standardized institutional protocols. Representative intraoperative photographs illustrating each surgical step are presented for methodological purposes, whereas the corresponding clinical outcomes are reported in the Results section. Detailed clinical documentation of the representative case, including anterior segment findings, intraocular pressure measurements, and imaging data, is provided in **Supplement No. 1**.

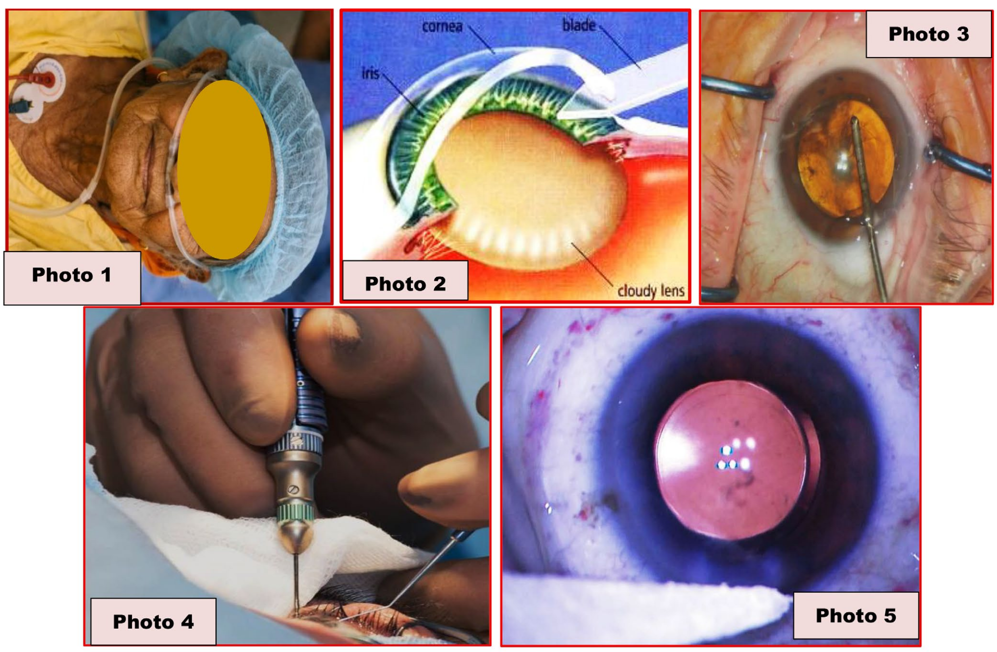

Figure 2. The sequential surgical steps of conventional phacoemulsification surgery.

2.5. Artificial Intelligence Methodology Analysis and Techniques Used in Cataract Surgery

2.5.1. Artificial Intelligence Methodology Analysis

Artificial intelligence (AI) methodology in the present study comprised AI-assisted biometric analysis for IOL power calculation and AI-supported OCT interpretation. Ocular biometric parameters, including axial length, keratometry, and anterior chamber depth, were acquired using optical biometry and analyzed with commercially available AI-based IOL calculation methods, specifically the Hill-RBF algorithm and the PEARL-DGS formula. These ML-based algorithms, trained on large postoperative refractive datasets, integrate biometric variables, IOL characteristics, and postoperative refractive outcomes to identify predictive patterns that improve refractive accuracy, particularly in eyes with anatomical variability and in elderly patients.

The AI-assisted biometric workflow consisted of: **1)** acquisition of biometric measurements; **2)** input of biometric data into AI-based formulas; **3)** algorithmic prediction of optimal IOL power; **4)** cross-validation of AI-generated results with conventional formulas (e.g., SRK/T); and **5)** final surgeon-guided selection of the IOL power aimed at achieving postoperative emmetropia. The final IOL power was independently confirmed by the operating cataract surgeon, while AI-generated calculations served exclusively as clinical decision-support tools and did not replace clinical judgment (**Figure 3:** Photo 6) [18] (***Accuracy and precision of intraocular lens calculations using the new Hill-RBF version 2.0 in eyes…***) ***and*** [19] (***AI and advanced technology in surgery…***).

In addition, AI assisted OCT analysis was performed to evaluate retinal and macular integrity before surgery. High-resolution cross-sectional retinal images were obtained using spectral-domain OCT and analyzed through deep learning algorithms that automatically segmented retinal layers, quantified macular thickness and retinal architecture, detected subtle abnormalities such as epiretinal membranes or macular edema, generated probability maps for retinal pathology, and subsequently underwent clinical validation by the ophthalmic surgeon.

Within the present study, AI-assisted image analysis confirmed normal retinal morphology and the absence of clinically significant posterior segment pathology (***Supplement 2***), thereby excluding contraindications to cataract surgery and supporting preoperative surgical planning and prediction of postoperative visual outcomes (**Figure 3:** Photo 7).

2.5.2. Techniques and Devices Used in the Clinical Study of AI-Assisted Cataract Surgery

Artificial intelligence (AI) was incorporated into the clinical workflow as a decision-support tool to assist diagnostic evaluation, preoperative planning, intraoperative guidance, and postoperative assessment of patients undergoing cataract surgery. The AI-assisted workflow combined automated image analysis with digital surgical planning to improve the standardization and efficiency of clinical decision-making.

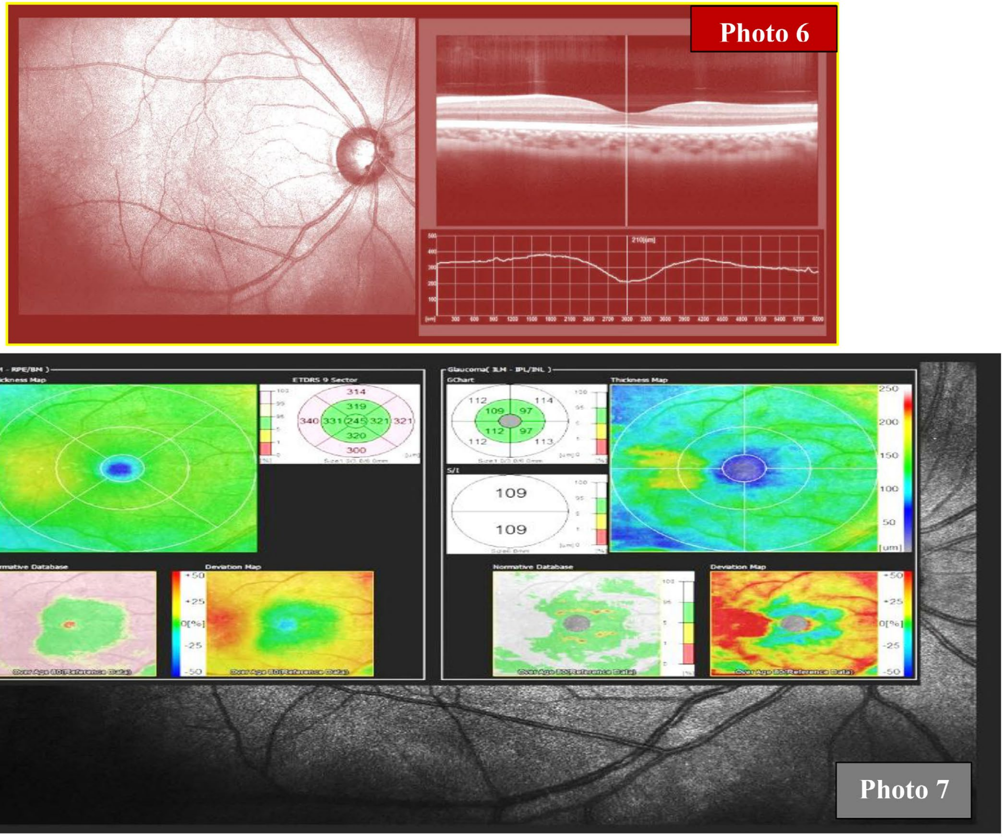

Figure 3. AI-based biometric analysis, IOL power calculation, and OCT interpretation.

All image acquisitions were performed according to the manufacturer's standardized scanning protocol by experienced ophthalmic personnel at the "Albanian Eye Center" [14], and all examinations met the quality criteria recommended by the manufacturer before inclusion in the analysis. All cataract procedures were performed using the *Constellation® Vision System* (Alcon Laboratories, Fort Worth, TX, USA) according to standard phacoemulsification techniques through a 2.4-mm clear corneal incision. Preoperative ocular biometry was obtained using the IOL Master 700 (Carl Zeiss Meditec AG, Jena, Germany). Biometric measurements included axial length, keratometry, anterior chamber depth, lens thickness, central corneal thickness, and white-to-white distance. These parameters were used for surgical planning, intraocular lens (IOL) power calculation, and refractive prediction. Macular and retinal assessment was performed using *Optiva Spectral-Domain Optical Coherence Tomography* (*SD-OCT*) (Optiva Inc., Fremont, CA, USA) whenever clinically indicated to exclude macular pathology and optimize preoperative evaluation. Surgical planning incorporated a predefined surgeon-specific *Surgically Induced Astigmatism* (*SIA*) value corresponding to the standard 2.4-mm clear corneal incision. The SIA value was integrated into the preoperative calculations to improve postoperative refractive accuracy and minimize residual astigmatism. IOL power was calculated using the *ESCRS Online IOL Calculator* together with validated biometric formulas selected according to the patient's ocular characteristics. *SRK/T* was preferentially used for eyes with long axial length and high myopia, whereas *Hoffer Q* was applied for eyes with short axial length and hyperopia. *Barrett Universal II*, *Haigis*, *and Holladay* 2 formulas were selected when clinically appropriate according to axial length, keratometry, anterior chamber depth, lens thickness, corneal astigmatism, and the surgeon's clinical judgment. The AI-supported workflow incorporated advanced digital ocular biometry, OCT-guided imaging, computer-assisted biometric analysis, digital surgical planning, and image-guided refractive assessment to support preoperative planning and optimize surgical precision. These technologies were employed exclusively as clinical decision-support tools to assist biometric interpretation, refractive prediction, IOL power selection, surgical planning, and perioperative decision-making. Postoperative assessment included corrected distance visual acuity (CDVA), uncorrected visual acuity (UDVA), refractive accuracy, residual astigmatism, intraoperative stability, complication rates, and surgical standardization parameters. Statistical analyses were performed using IBM SPSS Statistics (Version 27, IBM Corp., Armonk, NY, USA), with statistical significance established at $P < 0.05$.

No proprietary or in-house artificial intelligence, machine learning, or deep learning model was developed, trained, or validated as part of this study. The study exclusively employed commercially available ophthalmic diagnostic devices, digital planning software, and validated biometric calculation tools routinely used in contemporary cataract surgery. AI-generated measurements and decision-support outputs were interpreted in conjunction with comprehensive clinical examination and established ophthalmic practice, ensuring that all clinical decisions reflected expert physician judgment rather than automated recommendations alone.

For illustrative methodological purposes, a representative clinical case involving a 73-year-old male patient (M.S.) residing in Kamza, Tirana, diagnosed with age-related nuclear cataract of the left eye (OS), is presented to illustrate the application of the AI-assisted diagnostic and surgical workflow. All clinical and imaging findings were systematically documented in the patient's medical record (**Supplement No. 2**).

2.5.3. AI-Assisted Phacoemulsification Procedure

AI-assisted phacoemulsification enhances preoperative planning, intraoperative guidance, and real-time clinical decision-making through data-driven analytics and image-recognition systems. These technologies are designed to support the ophthalmic surgeon by improving surgical precision, standardizing selected procedural steps, facilitating early recognition of potential complications, and optimizing visual outcomes.

1) *Preoperative assessment and planning*, advanced AI-algorithms analyze ocular imaging data (e.g., OCT, optical biometry, and corneal topography) to assist the surgeon in IOL selection and preoperative risk assessment. ML-based models optimize incision planning, IOL power calculation, and identify potential intraoperative challenges before surgery.

2) *Patient preparation and docking*, the eye is sterilized and stabilized according to the standard surgical protocol. AI-assisted image-guidance systems facilitate proper alignment and docking of femtosecond laser devices, ensuring optimal positioning based on real-time image analysis.

3) *Corneal incision*, a continuous curvilinear capsulorhexis is created under surgeon control with AI-assisted image guidance when available. AI-supported imaging assists in achieving optimal capsulotomy size, centration, and circularity, either during manual surgery or with femtosecond laser assistance.

4) *Capsulorhexis formation*, a continuous curvilinear capsulorhexis is created under surgeon control with AI-assisted image guidance when available. AI-supported imaging assists in achieving optimal capsulotomy size, centration, and circularity, either during manual surgery or with femtosecond laser assistance.

5) *Hydro dissection and hydro delineation*, balanced salt solution is injected to separate the lens nucleus from the capsule and the nucleus from the epinucleus. AI-assisted intraoperative monitoring may assist in evaluating fluid dynamics and identifying early signs of potential complications.

6) *Phacoemulsification* (*lens fragmentation and removal*), ultrasonic energy is delivered via the phaco-probe to emulsify the cataractous lens. AI-enhanced phaco-machines dynamically adjust energy levels, vacuum, and aspiration parameters in real time, minimizing thermal and mechanical damage to surrounding tissues.

7) *Cortical aspiration*, residual cortical material is removed using irrigation/aspiration handpieces. AI-supported monitoring systems may optimize aspiration parameters and provide real-time feedback to facilitate complete and safe cortical removal.

8) *IOL implantation*, the selected IOL is implanted into the capsular bag. AI-assisted image guidance may support verification of appropriate IOL centration, positioning, and alignment before completion of the procedure.

9) *Wound closure and final assessment*, the corneal incisions are hydrated and allowed to self-seal whenever appropriate. AI-assisted imaging systems may assist in verifying wound integrity, anterior chamber stability, and correct IOL positioning before completion of surgery.

10) *Postoperative monitoring*, AI-assisted analytical tools may integrate intraoperative and postoperative clinical data to support prediction of visual recovery, facilitate postoperative follow-up, and contribute to continuous optimization of surgical performance through data-driven clinical feedback.

Both conventional biometric formulas and AI-assisted analytical methods utilize extensive postoperative refractive datasets incorporating biometric variables, IOL characteristics, and clinical outcomes to improve refractive prediction and surgical planning. AI-based analytical systems identify complex empirical relationships that enhance predictive performance while supporting, rather than replacing, surgeon-led clinical decision-making [20] (***Optical coherence tomography retinal imaging: narrative review of technological advancements and clinical applications***) and [21] (***Artificial Intelligence and advanced technology in…***).

2.6. Comparative Analysis of Conventional and AI Assisted Cataract Surgery

A comprehensive assessment of baseline demographic, systemic, and ophthalmic characteristics was performed to establish the preoperative comparability of patients allocated to conventional and AI-assisted cataract surgery. Table 4 summarizes the distribution of these variables and the corresponding statistical comparisons between the two study groups.

Table 4. Baseline clinical characteristics of patients according to surgical group.

Variabla	Group 1 Conventional (n = 55)	Group 2 AI-assisted (n = 43)	*P*-value
Age (years), mean ± SD	53.7 + 7.4 (range 50 - 80 years)	51.4 + 6.9 (range, 45 - 76 years)	0.116
Female, n (%) 55 patients	34 patients (61.8%)	21 patients (48.8%)	0.199
Male, n (%)	21 patients (38.2%)	22 patients (51.2%)	0.199*
Diabetes mellitus, n (%)	7 patients (12.7%)	8 patients (18.6%)	0.423
Hypertension, n (%)	23 patients (41.8%)	17 patients (39.5%)	0.819
Cardiovascular disease, n (%)	29 patients (52.7%)	14 patients (32.6%)	0.046
Unilateral cataract, n (%)	50 patients (90.9%)	37 patients (86.0%)	0.449
Bilateral cataract, n (%)	5 patients (9.1%)	6 patients (14%)	0.449
Symptom duration (days), mean ± SD	13.2 ± 5.6 days	15.3 ± 4.5 days	0.042
Baseline visual acuity (VA), mean ± SD	0.72 ± 0.31 logMAR.	0.65 ± 0.30 logMAR	0.262
Baseline intraocular pressure (IOP), mean ± SD	15.2 ± 3.4 mmHg	15.5 ± 3 mmHg	0.644

The mean age of patients was comparable between the conventional and AI-assisted surgery groups (53.7 ± 7.4 vs. 51.4 ± 6.9 years, $P = 0.116$). Similarly, no statistically significant difference was observed in sex distribution, although the conventional surgery group included a slightly higher proportion of female patients than the AI-assisted group (61.8% vs. 48.8%, $P = 0.199$).

With regard to systemic comorbidities, the prevalence of diabetes mellitus and hypertension was comparable between the two groups, with no statistically significant differences ($P = 0.423$ and $P = 0.819$, respectively). However, cardiovascular disease was significantly more frequent among patients undergoing conventional cataract surgery than among those treated with the AI-assisted approach (52.7% vs. 32.6%, $P = 0.046$).

Baseline ophthalmic characteristics were also largely comparable. No statistically significant differences were identified in the distribution of unilateral and bilateral cataracts ($P = 0.449$), baseline visual acuity (0.72 ± 0.31 vs. 0.65 ± 0.30 logMAR, $P = 0.262$), or baseline intraocular pressure (15.2 ± 3.4 vs. 15.5 ± 3.0 mmHg, $P = 0.644$). In contrast, preoperative symptoms duration before surgery, was significantly longer in the AI-assisted group than in the conventional surgery group (15.3 ± 4.5 vs. 13.2 ± 5.6 days, $P = 0.042$).

Overall, the two study groups demonstrated a broadly comparable baseline profile, with statistically significant differences identified only for cardiovascular disease prevalence and symptom duration before surgery.

The selection of study variables was guided by the primary study objective and informed by evidence from previously published studies. In particular, the methodological framework and comparative parameters were adapted from the studies of Lauren E. Chen *et al.* and Paulina N. Truong *et al.*, which evaluated the performance of conventional and AI-assisted cataract surgery across multiple clinical and operational domains. Based on these findings, the present study incorporated variables related to patient baseline characteristics, surgical performance, clinical outcomes, and procedure-related factors to enable a comprehensive comparison between the two surgical approaches. Previous evidence has consistently demonstrated that AI-assisted cataract surgery offers significant advantages in terms of surgical precision, predictive accuracy, and consistency of clinical outcomes. Nevertheless, the literature also identifies several challenges associated with its implementation, including higher acquisition and maintenance costs [22] (***Comparison of cost-utility, visual acuity, and humanistic outcomes of cataract surgery… in the USA vs International outreach campaigns***)„ limited accessibility in resource-constrained healthcare settings [23] (***Tools and methods for cataract recognition in low-resource settings: A narrative…***) and the requirement for specialized training and substantial surgical experience to ensure its effective integration into routine clinical practice.

2.7. Statistical Analysis

Statistical analyses were performed according to the predefined study objectives and endpoints. Baseline demographic, clinical, and ophthalmic characteristics were compared to assess the comparability of the conventional and AI-assisted cataract surgery groups before intervention. Functional outcomes were evaluated by analyzing changes in visual acuity from the preoperative examination to the 6-month postoperative follow-up, while physiological outcomes were evaluated through changes in intraocular pressure over the same period. Surgical effectiveness was assessed by comparing anatomical success rates and the need for secondary interventions, whereas safety outcomes were evaluated by analyzing postoperative complications. The statistical methods applied to each predefined endpoint, together with the corresponding comparison and assessment time point, are summarized in **Table 5**.

Table 5. Statistical methods applied according to the predefined study objectives and endpoints.

Study objective	Study endpoint	Variable	Comparison	Time point	Statistical test
Baseline comparability	Demographic characteristics	Age (years)	Conventional vs. AI-assisted	Baseline	Independent-samples *t*-test
		Sex (female/male)	Conventional vs. AI-assisted	Baseline	Pearson's χ^2 test
	Clinical characteristics	Diabetes mellitus	Conventional vs. AI-assisted	Baseline	Pearson's χ^2 test
		Hypertension	Conventional vs. AI-assisted	Baseline	Pearson's χ^2 test
		Cardiovascular disease	Conventional vs. AI-assisted	Baseline	Pearson's χ^2 test
	Ocular characteristics	Cataract laterality (unilateral/bilateral)	Conventional vs. AI-assisted	Baseline	Pearson's χ^2 test
		Symptom duration (days)	Conventional vs. AI-assisted	Baseline	Independent-samples *t*-test
		Baseline visual acuity (VA)	Conventional vs. AI-assisted	Baseline	Independent-samples *t*-test
		Baseline intraocular pressure (IOP)	Conventional vs. AI-assisted	Baseline	Independent-samples *t*-test
Functional effectiveness	Visual outcome	Visual acuity (VA)	Preoperative vs. postoperative	6-month follow-up	Paired *t*-test
		Postoperative visual acuity	Conventional vs. AI-assisted	6-month follow-up	Independent-samples *t*-test
Physiological effectiveness	Intraocular pressure	(IOP)	Preoperative vs. postoperative	6-month follow-up	Paired *t*-test
		Postoperative intraocular pressure	Conventional vs. AI-assisted	6-month follow-up	Independent-samples *t*-test
Surgical effectiveness and safety	Surgical performance	Primary anatomical success	Conventional vs. AI-assisted	Final follow-up	Pearson's χ^2 test
		Need for secondary intervention	Conventional vs. AI-assisted	Final follow-up	Pearson's χ^2 test
	Safety profile	Postoperative complications	Conventional vs. AI-assisted	Throughout follow-up	Fisher's exact test*
		Final anatomical success	Conventional vs. AI-assisted	Final follow-up	Pearson's χ^2 test

Abbreviations: VA, visual acuity; IOP, intraocular pressure. *Fisher's exact test was applied when the expected frequency in any contingency table cell was < 5; otherwise, Pearson's χ^2 test was used. All statistical tests were two-sided, and statistical significance was defined as a two-sided P value < 0.05.

Continuous variables were expressed as mean ± standard deviation (SD) or median (interquartile range [IQR]), depending on data distribution, whereas categorical variables were summarized as frequencies and percentages. Independent-samples *t*-tests were used to compare continuous variables between the conventional and AI-assisted groups, whereas paired *t*-tests were applied to evaluate within-group changes between preoperative and postoperative measurements. Categorical variables were analyzed using Pearson's χ^2 test or Fisher's exact test, as appropriate. Missing data were handled using complete-case analysis, whereby only participants with complete information for the variables under investigation were included in the corresponding analyses. All statistical analyses were performed using IBM SPSS Statistics (Version 27; IBM Corp., Armonk, NY, USA). A two-sided P value < 0.05 was considered statistically significant.

3. Results

3.1. Demographic Findings and Clinical Characteristics

A total of 98 patients who underwent cataract surgery between May 2019 and April 2026 were included in the analysis. Based on the diagnostic and surgical workflow employed, patients were categorized into two comparative groups.

The conventional group (***Group A***) comprised 55 patients who underwent cataract surgery between May 2019 and April 2023 using standard diagnostic assessment and conventional surgical techniques without artificial intelligence (AI) assistance. The AI-assisted group (***Group B***) included 43 patients treated between October 2023 and April 2026 using an AI-integrated diagnostic and surgical workflow.

Baseline demographic and clinical characteristics of both study groups were compared to establish between-group comparability before evaluating surgical performance, refractive outcomes, and postoperative clinical outcomes.

3.1.1. Baseline Demographic Characteristics

A total of 98 patients with age-related cataract undergoing primary cataract surgery were included in the study. The study cohort comprised 55 females (56.1%) and 43 males (43.9%). Most participants resided in rural areas (65.3%, n = 64), whereas 34.7% (n = 34) were from urban regions of Albania and Kosovo, reflecting the geographical referral pattern of the study center.

Participants ranged in age from 45 to 80 years. As shown in Table 2, the largest proportion of patients belonged to the 45 - 69-year age group (49.0%, n = 48), followed by the 70 - 75-year group (35.7%, n = 35) and the 76 - 80-year group (15.3%, n = 15). Age distribution was similar between female and male participants, with most patients of both sexes belonging to the youngest age category.

A detailed comparison of baseline demographic and clinical characteristics between the conventional and AI-assisted cataract surgery groups is presented in Table 4.

3.1.2. Age and Gender Distribution

According to the Data Presented in Table 2, gender distribution (57% female vs. 43% male) did not differ significantly between the conventional and AI-assisted groups (Pearson's χ^2 test, $P = 0.53$). Similarly, the distribution of patients according to place of residence (65% rural vs. 35% urban) was comparable between groups ($P = 0.47$), indicating good indicating good baseline demographic homogeneity and supporting the comparability of the two study groups before outcome analysis.

3.1.3. Group Comparability

Although the two study groups were comparable in size, minor differences in gender distribution were observed. The conventional surgery group included a slightly higher proportion of female patients, whereas the AI-assisted group included a relatively higher proportion of male patients. However, these differences were not statistically significant ($P > 0.05$), indicating good baseline comparability between the two study groups. Overall, baseline characteristics and clinical characteristics support the validity of subsequent comparisons of surgical performance and postoperative outcomes [24] (***Effect of trabeculectomy on the rate of progression of visual field damage***).

Across both study groups, primary anatomical success was achieved in 84% of patients, whereas complete final anatomical success (100%) was obtained after completion of follow-up. Most patients experienced postoperative visual improvement, and no severe intraoperative or postoperative complications resulting in permanent visual loss were recorded. A comprehensive comparison of demographic characteristics, clinical variables, surgical performance, and postoperative outcomes between the conventional and AI-assisted groups is presented in Table 6.

Table 6. Comparative summary of baseline characteristics, surgical workflow, and clinical outcomes in the conventional and AI-assisted cataract surgery.

Parameter/Variable	Overall Cohort (n = 98)	Conventional Surgery Group	AI-Assisted Surgery Group	Interpretation/Clinical Significance
Sample size	98 patients	Comparable subgroup	Comparable subgroup	Balanced grouping ensures valid comparative analysis between techniques.
Mean age (years)	55.6 ± 9.8 (range 45 - 80)	No significant difference	No significant difference	Age homogeneity (**$P = 0.41$**) indicates outcomes are not age-biased. Case examples reflect elderly subgroup relevance.
Gender distribution	57% female (n = 55)/43% male (n = 43)	Slight female predominance	Slight male predominance	No statistical difference (**$P = 0.53$**).
Residence	65% rural/35% urban	Similar distribution	Similar distribution	Similar distribution between study groups.
Group comparability	Homogeneous baseline	Slightly more females	Slightly more males	Comparable baseline (**$P > 0.05$**) characteristics support valid comparison of postoperative outcomes.
Case study profile	—	81 year-old female, mature cataract (OU)	73 year-old male, nuclear cataract (OS)	Conventional case represents advanced cataract complexity; AI case reflects earlier-stage precision-driven intervention.
Preoperative assessment	Standardized across cohort	Clinical + basic biometry	AI enhanced biometry + OCT analysis	AI-assisted workflow incorporated advanced biometry and OCT analysis.

Continued

IOL power calculation	Standard formula applied	SRK/T and similar	Hill-RBF, PEARL-DGS + validation	AI-assisted workflow incorporated Hill-RBF and PEARL-DGS formulas together with conventional validation.
Surgical planning	Protocol-based	Surgeon dependent	AI-assisted predictive modeling	Protocol-based vs AI-assisted predictive planning.
Intraoperative precision	High overall	Manual technique (phacoemulsification)	AI-guided/laser-assisted steps	Manual phacoemulsification versus AI-supported workflow.
Phacoemulsification control	Effective in all cases	Surgeon controlled parameter	Real-time AI parameter optimization	Real-time optimization of surgical parameters in the AI-assisted workflow.
Complication rate	No severe complications reported	Minimal	Minimal to lower	No severe complications in either group.
Primary success rate	84%	Comparable	Comparable or slightly higher	Comparable primary success.
Final success rate	100%	100%	100%	Both techniques achieve excellent final outcomes.
Visual improvement	Majority improved	Significant improvement	Potentially more predictable outcomes	Postoperative visual improvement observed in both groups.

3.2. Comparative Analysis: Conventional vs AI Assisted Cataract Surgery

A comparative evaluation was performed to assess the relative performance of conventional and AI-assisted cataract surgery with respect to surgical planning, intraoperative guidance, predictive capability, management of complex cases, and overall clinical performance.

3.2.1. Surgical Planning and Refractive Accuracy

AI-assisted cataract surgery demonstrated significantly greater refractive accuracy than the conventional approach. The use of AI-supported biometric analysis and IOL power calculation was associated with improved procedural standardization through real-time decision support and enhanced intraoperative guidance. These findings suggest that AI-assisted preoperative planning improved refractive predictability compared with conventional biometric methods.

3.2.2. Intraoperative Performance

In the conventional surgery group, intraoperative performance depended primarily on the surgeon's experience and manual execution, without automated intraoperative support. In contrast, the AI-assisted workflow enhanced procedural standardization by providing real-time decision support and image-guided intraoperative assistance, thereby contributing to greater surgical consistency.

3.2.3. Predictive Capability of Complications and Outcome Consistency

Compared with conventional cataract surgery, the AI-assisted approach demonstrated greater predictive capability by supporting preoperative risk assessment and postoperative outcome prediction. Furthermore, surgical outcomes in the AI-assisted group were more consistent owing to algorithm-supported standardization, whereas greater variability was observed in the conventional group because of operator-dependent factors [25] (***AI in glaucoma, advances in diagnosis, progression forecasting and surgical outcome prediction***).

3.2.4. Complex Case Management

Conventional cataract surgery remained more adaptable for managing anatomically complex cases and coexisting ocular conditions, relying primarily on the surgeon's clinical expertise and intraoperative judgment. Although the AI-assisted workflow offered several advantages in surgical planning and procedural standardization, its broader implementation remained dependent on the availability of high-quality datasets and externally validated algorithms.

3.3. Functional, Physiological, and Surgical Outcomes of the Study Participants (Table 7)

Primary anatomical success was achieved in 84% of patients (95% CI: 75.2 - 90.1). Following secondary interventions, complete anatomical success (100%) was achieved in both the conventional and AI-assisted groups at the final follow-up (95% CI: 96.3 - 100). Because identical final anatomical outcomes were observed in both groups, no between-group statistical comparison was performed for this endpoint. Overall, both surgical approaches achieved complete anatomical recovery by the end of the follow-up period.

3.3.1. Functional Outcomes

Visual acuity, both surgical techniques resulted in significant postoperative improvement in visual acuity compared with baseline measurements. In the conventional surgery group, the mean improvement in visual acuity was 0.42 ± 0.15 (decimal scale; $P < 0.001$), whereas the AI-assisted group demonstrated significantly a greater mean improvement of 0.51 ± 0.13 ($P < 0.001$). Between-group comparison demonstrated significantly greater visual improvement following AI-assisted cataract surgery (mean difference: 0.09; 95% CI: 0.03 - 0.15; $P = 0.004$), indicating superior postoperative functional visual outcomes.

3.3.2. Physiological Outcomes

Intraocular pressure, transient postoperative elevation of intraocular pressure (IOP) occurred in both groups and was successfully managed with standard postoperative treatment. The incidence was 18% (95% CI: 9.8 - 30.8) in the conventional surgery group and 15% (95% CI: 7.2 - 28.8) in the AI-assisted group, with no statistically significant difference between groups ($P = 0.68$). No patient developed persistent ocular hypertension or long-term IOP-related complications throughout the follow-up period.

3.3.3. Surgical Performance

Refractive accuracy, AI-assisted cataract surgery demonstrated significantly greater refractive accuracy than the conventional approach. Achievement of the target postoperative refraction (±0.5 diopters) was observed in 71% of patients in the conventional surgery group (95% CI: 57.3 - 82.1) and 87% of patients in the AI-assisted group (95% CI: 73.2 - 94.4). The absolute difference of 16 percentage points was statistically significant ($P = 0.03$), supporting superior refractive predictability with the AI-assisted approach.

3.3.4. Intraoperative Efficiency

The mean surgical time was 18.5 ± 4.2 minutes for conventional cataract surgery and 15.9 ± 3.6 minutes for AI-assisted surgery. The mean reduction of 2.6 minutes (95% CI: −4.1 to −1.1; $P = 0.001$) demonstrated significantly shorter operative time and improved procedural efficiency in the AI-assisted group.

Table 7. Comparative functional, physiological, and surgical outcomes according to surgical technique.

Outcome domain	Outcome measure	Conventional surgery (n = 55)	AI-assisted surgery (n = 43)	Statistical outcome	Clinical interpretation
Surgical effectiveness	High primary anatomical success was observed in both groups.	Included in the overall success rate (84%)	Included in the overall success rate (84%)	—	High primary anatomical success was achieved in both groups.
	Final anatomical success	100% (95% CI: 96.3 - 100)	100% (95% CI: 96.3 - 100)	Not applicable (identical outcome)	Complete anatomical recovery was achieved in both groups at the final follow-up.
Functional effectiveness	Improvement in visual acuity	0.42 ± 0.15	0.51 ± 0.13	Mean difference: 0.09 (95% CI: 0.03 - 0.15); $P = 0.004$	AI-assisted surgery resulted in significantly greater visual improvement.
Physiological effectiveness	Transient postoperative IOP elevation	18% (95% CI: 9.8 - 30.8)	15% (95% CI: 7.2 - 28.8)	$P = 0.68$	Comparable postoperative IOP control in both groups.
Surgical performance	Target refraction (±0.5 D) achieved	71% (95% CI: 57.3 - 82.1)	87% (95% CI: 73.2 - 94.4)	Difference: +16%; $P = 0.03$	AI-assisted surgery provided greater refractive accuracy.
	Mean surgical time (minutes)	18.5 ± 4.2	15.9 ± 3.6	Mean difference: −2.6 min (95% CI: −4.1 to −1.1); $P = 0.001$	AI-assisted surgery significantly improved procedural efficiency
Safety profile	Mild postoperative complications	23% (95% CI: 13.5 - 36.1)	19% (95% CI: 10.1 - 32.4)	$P = 0.64$	Similar incidence of mild complications in both groups.
	Severe vision-threatening complications	None	None	Not applicable	No severe complications were observed in either group.

3.3.5. Safety Profile

No severe intraoperative or postoperative complications leading to permanent visual loss were observed in either group. Mild postoperative complications, including transient corneal edema and temporary IOP elevation, occurred in 23% of patients in the conventional surgery group (95% CI: 13.5 - 36.1) and 19% of patients in the AI-assisted group (95% CI: 10.1 - 32.4), with no statistically significant difference between groups ($P = 0.64$). Overall, both surgical approaches demonstrated a favorable safety profile.

4. Discussions

4.1. Principal Findings

The present comparative study demonstrated that both conventional phacoemulsification and AI-assisted cataract surgery achieved excellent anatomical and functional outcomes. Complete anatomical success was achieved in both groups at the final follow-up, while AI-assisted cataract surgery demonstrated significantly greater refractive accuracy, improved postoperative visual acuity, and shorter operative time compared with the conventional approach. No significant differences were observed in postoperative complication rates, indicating that both techniques were associated with a favorable safety profile. The principal contribution of this study is demonstrating that artificial intelligence enhances cataract surgery primarily through improved surgical planning, predictive analytics, and procedural standardization rather than replacing the clinical expertise and intraoperative judgment of experienced ophthalmic surgeons.

4.2. Interpretation of the Findings and Comparison with Previous Studies

The improved refractive accuracy observed in the AI assisted group is consistent with the increasing use of ML based biometric formulas, such as Hill-RBF and PEARL-DGS, which integrate large postoperative datasets to optimize intraocular lens power prediction. Improved refractive predictability is particularly relevant in eyes presenting with anatomical variability, where conventional biometric formulas may demonstrate reduced accuracy. Similarly, the shorter operative time observed in the AI-assisted group most likely reflects improved preoperative planning and a more standardized intraoperative workflow rather than changes in the surgical technique itself. AI supported biometric analysis and digital planning facilitate more standardized surgical execution while maintaining surgeon supervision throughout the procedure. Importantly, although AI assisted surgery demonstrated superior refractive predictability and greater consistency of clinical outcomes, conventional phacoemulsification remained highly effective, particularly in anatomically complex cataracts where surgeon experience and intraoperative judgment continue to represent the principal determinants of surgical success.

4.3. Clinical Implications

The present findings support the concept that AI should be considered a complementary clinical technology rather than an autonomous surgical system. AI assisted platforms provide decision support during preoperative evaluation, biometric interpretation, intraocular lens selection, and perioperative planning, whereas final clinical decisions remain dependent on surgeon expertise. From a practical perspective, the integration of AI into routine cataract surgery may improve surgical standardization, reduce variability in refractive outcomes, and facilitate individualized patient management without compromising surgical safety. Consequently, the optimal future model of cataract surgery is likely to integrate advanced AI supported technologies with the experience and clinical judgment of ophthalmic surgeons.

4.4. Study Strengths and Limitations

The present study has several strengths. It provides a direct comparison between conventional and AI assisted cataract surgery performed at the single tertiary ophthalmic center using standardized surgical protocols and comprehensive postoperative evaluation. Furthermore, multiple clinically relevant outcomes measures including visual acuity, refractive accuracy, intraocular pressure, operative efficiency, and safety were evaluated simultaneously, providing a comprehensive assessment of AI assisted cataract surgery. Nevertheless, several limitations should be acknowledged. ***First***, the retrospective non-randomized, before and after study design may have introduced confounding related to the calendar period because the conventional and AI assisted groups were treated during different time intervals. ***Second***, progressive improvement in surgeon experience during the study period may have influenced surgical outcomes independently of AI assisted technologies. ***Third***, although baseline demographic and clinical characteristics were generally comparable, residual differences in case mix cannot be completely excluded. ***Finally***, continuous advances in diagnostic imaging, biometric devices, intraocular lens calculation methods, and perioperative management throughout the study period may also have contributed to the observed improvements. Therefore, the present findings should be interpreted as demonstrating an association between AI assisted cataract surgery and improved clinical outcomes rather than establishing a direct causal relationship. Future prospective randomized, multicenter studies with larger patient populations and longer follow-up period are warranted to further validate these findings.

5. Conclusions

* The present comparative study demonstrated that both conventional phacoemulsification and AI-assisted cataract surgery achieved excellent clinical outcomes with a favorable safety profile. Although complete anatomical success was achieved in both groups, the AI-assisted approach was associated with greater refractive accuracy, improved postoperative visual acuity, and shorter operative time, indicating enhanced surgical precision and procedural efficiency.

* These findings suggest that AI represents a valuable clinical decision-support technology for cataract surgery by improving biometric analysis, surgical planning, refractive predictability, and perioperative standardization. Nevertheless, AI should be regarded as a complementary clinical tool rather than a substitute for the expertise, clinical judgment, and intraoperative decision-making of experi-

enced ophthalmic surgeons. Conventional phacoemulsification remains indispensable, particularly in anatomically complex cases that require individualized surgical management.

* Because of the retrospective, non-randomized study design, the observed differences should be interpreted as demonstrating an association rather than a direct causal relationship between AI-assisted technologies and improved clinical outcomes. Future prospective, randomized, multicenter studies with larger patient populations and longer follow-up periods are warranted to further validate the long-term effectiveness, safety, and cost-effectiveness of AI-assisted cataract surgery.

6. Recommendations

Based on the findings of the present study, the following recommendations are proposed.

* Artificial intelligence should be integrated into routine cataract surgery as a clinical decision-support tool to improve preoperative biometric assessment, IOL power calculation, surgical planning, and postoperative outcome prediction. Nevertheless, final clinical decision-making and surgical management should remain the responsibility of experienced ophthalmic surgeons, particularly in anatomically complex cases. A hybrid clinical model combining AI-assisted technologies with surgeon expertise is recommended to optimize patient outcomes.

* Future prospective, multicenter, randomized controlled studies involving larger patient populations and longer follow-up periods are recommended to further evaluate the long-term effectiveness, safety, cost-effectiveness, and clinical applicability of AI-assisted cataract surgery. Additional research should also investigate the role of emerging machine learning algorithms in personalized surgical planning, intraoperative decision support, and postoperative outcome prediction.

* Healthcare institutions and policymakers should promote equitable access to cataract screening, diagnostic imaging, and surgical services, particularly for underserved and rural populations. Strategic investment in AI-supported ophthalmic technologies, together with standardized clinical training and evidence-based implementation, may facilitate the safe, effective, and equitable integration of artificial intelligence into routine ophthalmic practice.

Ethics approval and consent to participate**,** this study was conducted in accordance with the ethical principles of the Declaration of Helsinki. It was designed as a retrospective, non-randomized comparative study based exclusively on the secondary analysis of existing anonymized clinical records of patients who underwent cataract surgery at the Albanian Eye Center (AEC), Tirana, Albania, between May 2019 and April 2026. No prospective patient recruitment, study-specific intervention, or additional data collection was performed.

According to the Institutional review and ethics waiver statement issued by the Faculty of Medicine, University of Medicine, Tirana, Albania, formal review and approval by an Institutional Review Board (IRB) or an independent Ethics Committee were waived in accordance with institutional policy and applicable national regulations. The waiver applied to the entire study because it involved the retrospective secondary analysis of fully anonymized existing clinical data without direct patient contact, participant recruitment, or any study-related intervention.

Written informed consent for clinical examination, treatment, and the use of anonymized clinical data for research and scientific publication was obtained from all patients at the time of routine clinical care. Where clinical photographs or imaging were included in the supplementary materials, their publication was covered by the patients' informed consent for the use of anonymized clinical documentation for scientific and educational purposes. All clinical records and images were irreversibly anonymized prior to analysis and publication, ensuring the protection of patient privacy and confidentiality. No personally identifiable information was accessed, collected, or reported at any stage of the study.

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Author Contributions

Conceptualization, surgical procedures, supervision, and critical revision were performed by Assoc. Prof. Ali Tonuzi, MD, PhD. Data collection, analysis, manuscript drafting, and literature review were conducted by Dr. Luan Qafmolla.

Data collection, data analysis, manuscript drafting, literature review, by Dr. Luan Qafmolla, Orjeta Tonuzi, MD, PhD and Migena Beqiri MD.

Conflicts of Interest

All the authors declare no conflict of interest related to study case report.

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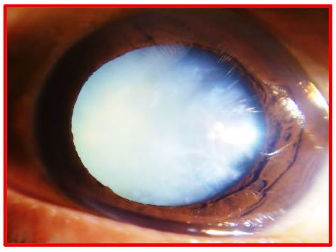
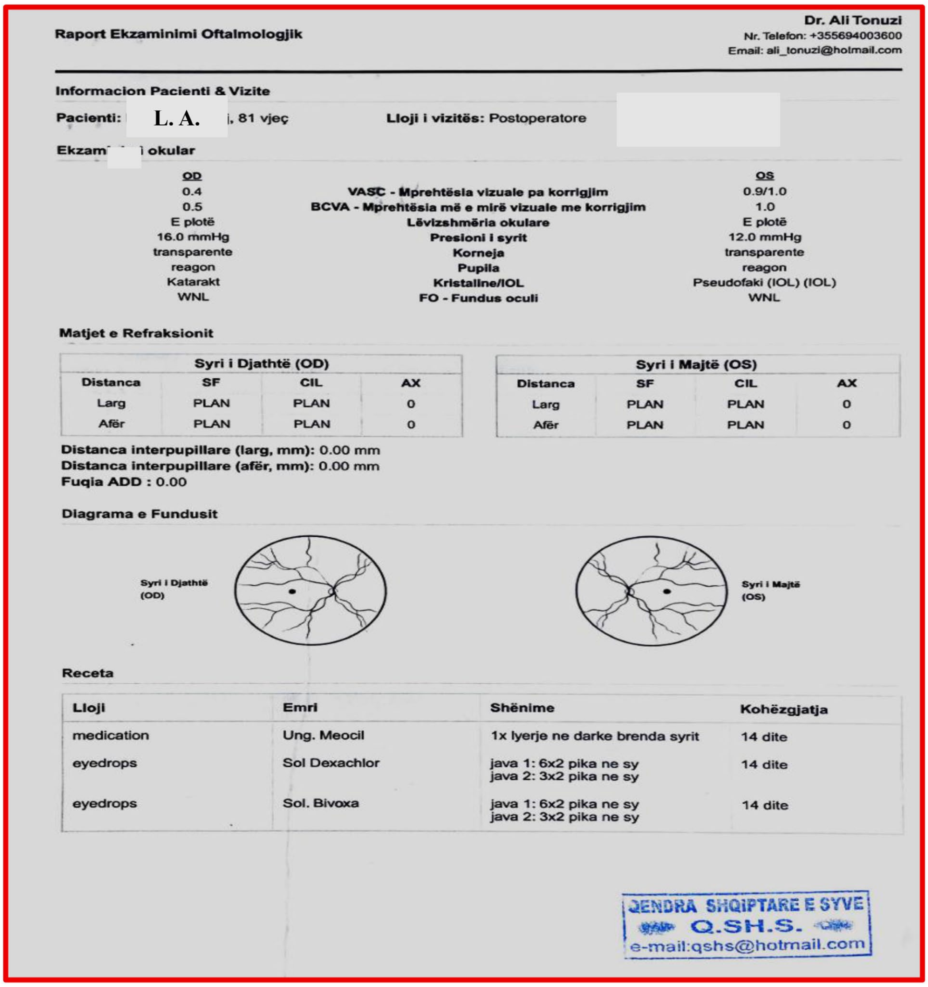
Supplement

Supplement No. 1

***First study case* of L.A. patient.** Upon examination, the following diagnoses observed:

Postoperative cataract*: DG: OD: Cataract senilis mature* and *DG: OS: Secondary glaucoma*





Raport Ekzaminimi Oftalmologjik

Dr. Ali Tonuzi
Nr. Telefon: +355694003600
Email: ali_tonuzi@hotmail.com

Informacion Pacienti & Vizite

Pacienti: L. A. i, 81 vjeç **Lloji i vizitës:** Postoperatore

Ekzami i okular

OD		OS
0.4	**VASC - Mprehtësia vizuale pa korrigjim**	0.9/1.0
0.5	**BCVA - Mprehtësia më e mirë vizuale me korrigjim**	1.0
E plotë	**Lëvizshmëria okulare**	E plotë
16.0 mmHg	**Presioni i syrit**	12.0 mmHg
transparente	**Korneja**	transparente
reagon	**Pupila**	reagon
Katarakt	**Kristaline/IOL**	Pseudofaki (IOL) (IOL)
WNL	**FO - Fundus oculi**	WNL

Matjet e Refraksionit

Syri i Djathtë (OD)			
Distanca	**SF**	**CIL**	**AX**
Larg	PLAN	PLAN	0
Afër	PLAN	PLAN	0

Syri i Majtë (OS)			
Distanca	**SF**	**CIL**	**AX**
Larg	PLAN	PLAN	0
Afër	PLAN	PLAN	0

Distanca interpupillare (larg, mm): 0.00 mm
Distanca interpupillare (afër, mm): 0.00 mm
Fuqia ADD : 0.00

Diagrama e Fundusit

Syri i Djathtë (OD)

Syri i Majtë (OS)

Receta

Lloji	Emri	Shënime	Kohëzgjatja
medication	Ung. Meocil	1x lyerje ne darke brenda syrit	14 dite
eyedrops	Sol Dexachlor	java 1: 6x2 pika ne sy java 2: 3x2 pika ne sy	14 dite
eyedrops	Sol. Bivoxa	java 1: 6x2 pika ne sy java 2: 3x2 pika ne sy	14 dite

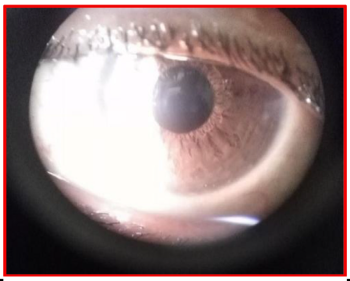
QENDRA SHQIPTARE E SYVE
Q.SH.S.
e-mail:qshs@hotmail.com

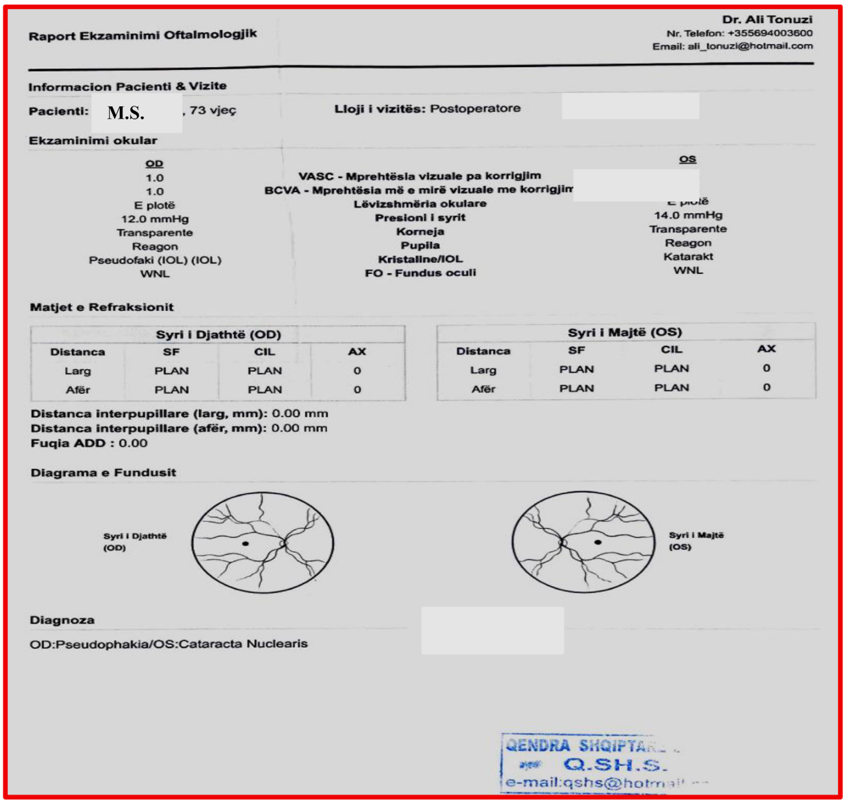
Postoperative cataract medical record of L.A. patient performed by conventional surgery.

Supplement No. 2

<u>Second study case</u>* *of M.S. patient. Upon examination, the following diagnoses observed:

Postoperative cataract*: DG: OD: Pseudophakia* and *DG: OS: Cataracta nuclearis*





Raport Ekzaminimi Oftalmologjik

Dr. Ali Tonuzi
Nr. Telefon: +355694003600
Email: ali_tonuzi@hotmail.com

Informacion Pacienti & Vizite

Pacienti: M.S., 73 vjeç **Lloji i vizitës:** Postoperatore

Ekzaminimi okular

OD		OS
1.0	**VASC - Mprehtësia vizuale pa korrigjim**	
1.0	**BCVA - Mprehtësia më e mirë vizuale me korrigjim**	
E plotë	**Lëvizshmëria okulare**	E plotë
12.0 mmHg	**Presioni i syrit**	14.0 mmHg
Transparente	**Korneja**	Transparente
Reagon	**Pupila**	Reagon
Pseudofaki (IOL) (IOL)	**Kristaline/IOL**	Katarakt
WNL	**FO - Fundus oculi**	WNL

Matjet e Refraksionit

Syri i Djathtë (OD)			
Distanca	**SF**	**CIL**	**AX**
Larg	PLAN	PLAN	0
Afër	PLAN	PLAN	0

Syri i Majtë (OS)			
Distanca	**SF**	**CIL**	**AX**
Larg	PLAN	PLAN	0
Afër	PLAN	PLAN	0

Distanca interpupillare (larg, mm): 0.00 mm
Distanca interpupillare (afër, mm): 0.00 mm
Fuqia ADD : 0.00

Diagrama e Fundusit

Syri i Djathtë (OD)

Syri i Majtë (OS)

Diagnoza

OD:Pseudophakia/OS:Cataracta Nuclearis

QENDRA SHQIPTA...
Q.SH.S.
e-mail:qshs@hotm...

Postoperative cataract medical record of M.S. patient performed by AI surgery technology.