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ORIGINAL ARTICLE

Effect of femtosecond laser-assisted arcuate keratotomy versus toric intraocular lens implantation on correction of astigmatism in cataract surgery: a systematic review and meta-analysis

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Abstract

Purpose To compare the efficacy of femtosecond laser-assisted arcuate keratotomy (FSAK) combined with non-toric intraocular lens (IOL) implantation versus Toric IOL (TIOL) implantation in correcting corneal astigmatism in cataract patients.

Methods Relevant literature was searched in databases including PubMed, Web of Science, Cochrane Central Register of Controlled Trials (CENTRAL), and SinoMed. Data from the included studies were extracted. A meta-analysis was conducted to compare the correction performance of FSAK combined with non-toric IOL implantation and TIOL implantation using postoperative refractive astigmatism, correction index, and uncorrected distance visual acuity (UDVA) outcomes. Publication bias assessment and sensitivity analysis were also performed.

Results Five comparative studies were ultimately included in the meta-analysis. The TIOL group had smaller postoperative refractive astigmatism and a greater correction index compared to the FSAK group. The mean differences in postoperative refractive astigmatism and correction index between the two groups were −0.19D (95% CI = 0.12 to 0.26, $P < 0.01$, $I^2 = 7\%$) and −0.09 (95% CI = −0.18 to 0.00, $P = 0.04$, $I^2 = 0\%$), respectively. We found no statistically significant difference in UDVA between the two groups (95% CI = −0.01 to 0.11, $P = 0.09$, $I^2 = 70\%$).

Conclusions FSAK combined with non-toric IOL implantation was found to be less effective than TIOL implantation in correcting preoperative corneal astigmatism in cataract patients. The difference in the effectiveness of astigmatism correction between the two surgical methods seems to diminish, as the degree of preoperative corneal astigmatism decreases.

Keywords Femtosecond laser-assisted arcuate keratotomy · Toric intraocular lens · Astigmatism · Cataract · Correction

Introduction

Currently, a multitude of techniques are employed in clinical settings to address preexisting corneal astigmatism in cataract patients. Implantation of toric intraocular lenses (TIOLs) is a widely utilized approach that has demonstrated considerable efficacy and predictability [1]. Additionally, surgical methods such as astigmatic keratotomy (AK), the opposite clear corneal incision (OCCI), and limbal release incisions (LRI) of the cornea can be combined with non-toric IOL implantation to manage low to moderate corneal astigmatism [2–4]. With advancements in laser technology for ophthalmic clinical applications, femtosecond laser-assisted arcuate keratotomy (FSAK) has emerged as a viable option. Several studies have confirmed the safety and effectiveness of FSAK in correcting astigmatism in cataract patients [5–7]. The femtosecond laser also offers exceptional accuracy and predictability in customizing corneal

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incisions [8]. Compared to traditional manual AK, FSAK yields superior results in controlling corneal astigmatism and postoperative visual outcomes [9]. A previous meta-analysis comparing the effects of TIOL implantation and corneal incisional procedures on correcting astigmatism in cataract surgery found the former to be more effective [10]. However, the controversial results from related studies make it difficult to determine the differences in efficacy between FSAK and TIOL implantation [11, 12]. In light of this, we conducted a meta-analysis to summarize the effect of FSAK with non-toric IOL implantation versus TIOL implantation on the correction of corneal astigmatism in cataract patients.

Methods

A systematic review and meta-analysis were conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [13]. The protocol was registered in PROSPERO under the registration number CRD42023438100.

Literature search

Relevant literature was retrieved from databases such as PubMed, Web of Science, the Cochrane Central Register of Controlled Trials (CENTRAL), and SinoMed. The search terms utilized included "arcuate keratotomy," "astigmatic keratotomy," "astigmatic incisions," "arcuate incisions," and "femtosecond laser." The search query in PubMed was ((arcuate keratotomy) OR (astigmatic keratotomy) OR (astigmatic incisions) OR (arcuate incisions)) AND (femtosecond laser). No language restrictions were imposed. Reference lists from full-text articles were scrutinized to identify additional pertinent studies. The final search was conducted on June 15, 2023.

Inclusion and exclusion criteria

The inclusion criteria for the meta-analysis were as follows: (1) study design—comparative study; (2) population—cataract patients with preexisting corneal astigmatism; (3) intervention—FSAK combined with non-toric IOL implantation; (4) comparison—TIOL implantation; and (5) outcome measures—postoperative refractive astigmatism in diopters (D), visual outcomes, and correction index determined by calculating the ratio of the surgically induced astigmatic change (SIA) to target-induced astigmatism (TIA). Non-comparative trials, duplicate publications, and conference abstracts lacking available raw data were excluded from the analysis.

Data extraction and assessment of study quality

All retrieved studies were independently evaluated by two authors (J.Z. and L.H.). After the automatic elimination of duplicates using Endnote X9, the authors checked for any remaining duplicates and assessed the eligibility of the studies by screening their titles and abstracts. The full-text articles of all potentially relevant studies were examined according to the inclusion and exclusion criteria. If a study was deemed eligible for inclusion, relevant data were extracted from it. A customized form was utilized to record information such as author identification, year of publication, country of study, study design details, sample size, mean age, type of IOL, duration of follow-up, intervention characteristics, preoperative astigmatism, and outcomes. Two independent authors (J.Z. and L.H.) employed the Cochrane Collaboration Risk of Bias tool version 2 (RoB 2) and the Risk Of Bias In Non-randomized Studies-of Interventions (ROBINS-I) to assess the risk of bias in randomized controlled trials (RCTs) and non-randomized comparative studies, respectively [14]. Any disagreements in study selection and quality assessment were resolved through consultation with a third reviewer (J.X.Z.).

Data analysis

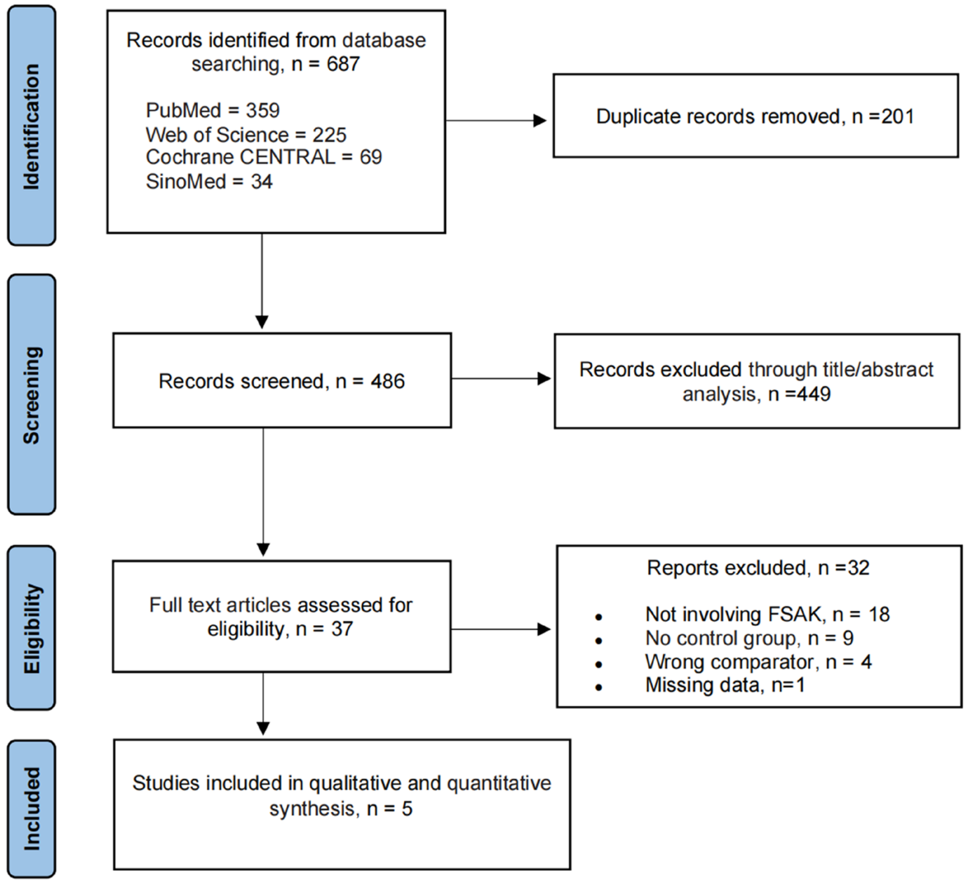
Data analysis was performed using Review Manager 5.4 software and R 4.2.1 software. Continuous variables were expressed as the mean difference (MD) with a 95% confidence interval (CI). The I^2 statistic was employed to estimate statistical heterogeneity among trials and to determine whether a fixed or random effects model should be used. A meta-analysis was conducted to compare the correction performance of FSAK combined with non-toric IOL implantation and TIOL implantation using postoperative refractive astigmatism, correction index, and uncorrected distance visual acuity (UDVA) outcomes. The summary results of the analysis were depicted using forest plots. Egger's test was utilized to assess the publication bias of the included studies. Additionally, a sensitivity analysis was conducted for all analyses to evaluate the influence of specific studies on the stability of the summary results. A P value less than 0.05 was considered statistically significant.

Results

Characteristics of included studies

The study selection process for the analysis is summarized in Fig. 1. The initial search yielded 687 relevant articles. After excluding duplicate literature and reviewing titles

Fig. 1 PRISMA flow chart



and abstracts, 37 full-text articles were further evaluated. Ultimately, five comparative studies were included in the qualitative and quantitative synthesis.

The characteristics of the five included studies are summarized in Table 1. These comprised one RCT and four non-randomized comparative studies. Two studies were conducted in China, two in Korea, and one in Spain. The preoperative corneal astigmatism inclusion criteria ranged from 0.50D to 4.50D. A total of 167 eyes received FSAK combined with non-toric IOL implantation, while 169 eyes received TIOL implantation. Table 2 presents the details of the FSAK procedure and the primary outcomes of the included studies. The follow-up duration ranged from 3 months to 1 year.

Assessment of study quality

The results of the risk of bias assessment for included studies are summarized in Fig. 2.

The RCT [12] had a low risk of bias for deviations from intended interventions, missing outcome data, and outcome measurement, but raised some concerns regarding the randomization process, selection of the reported result, and overall bias. The reason for concerns about randomization process in the RCT is that the information about randomization methods is just a statement that the study is randomized. For non-randomized studies, all [15–18] were found to have a moderate risk of confounding and overall bias. Three [15, 17, 18] were also at moderate risk of bias in the selection of the reported result. For the remaining domains, most studies were considered to have a low risk, except for one study [15] which lacked sufficient information to assess missing data bias.

Primary outcomes

Five studies involving 336 eyes and four studies involving 270 eyes were included to compare postoperative refractive astigmatism and correction index between the FSAK and TIOL groups, respectively. There was no significant heterogeneity, so a fixed effects model was used for the analysis. The forest plot is shown in Fig. 3. The mean differences in postoperative refractive astigmatism and correction index between the two groups were −0.19D (95% CI = 0.12 to 0.26, $P<0.01$, $I^2=7\%$) and −0.09 (95% CI = −0.18 to 0.00, $P=0.04$, $I^2=0\%$), respectively. The TIOL group had smaller

Table 1 The basic characteristics of the included studies

Author/Y	Country	Study design	Preoperative corneal astigmatism in inclusion criteria (D)	FSAK				TIOL			
				No of eyes	Mean age ± SD	Preoperative corneal astigmatism (D)	Preoperative refractive astigmatism (D)	No of eyes	Mean age ± SD	Preoperative corneal astigmatism (D)	Preoperative refractive astigmatism (D)
Hernandez 2022	Spain	RCT	1.25–3.00	37	73.08 ± 6.56	1.98 ± 0.35	NA	38	70.42 ± 8.26	2.12 ± 0.34	NA
Kwon 2021	Korea	Retrospective	0.75–2.00	27	69.4 ± 12.1	1.44 ± 0.39	1.85 ± 1.07	21	67.4 ± 12.5	1.50 ± 0.37	1.84 ± 0.81
Lin 2021	China	Retrospective	1.50–4.50	41	67.0 ± 13.3	1.64 ± 0.42	2.33 ± 1.43	53	67.2 ± 11.4	2.29 ± 0.91	3.44 ± 1.72
Noh 2021	Korea	Retrospective	0.50–4.50	35	61.54 ± 15.97	1.52 ± 0.67	1.52 ± 1.18	31	65.47 ± 15.91	1.70 ± 0.78	1.57 ± 1.19
Wang 2022	China	Retrospective	0.75–1.25	27	57.74 ± 2. 34	0. 855 ± 0. 088	NA	26	58.33 ± 1. 99	0. 860 ± 0. 082	NA

FSAK femtosecond laser-assisted arcuate keratotomy, *TIOL* toric intraocular lens, *D* diopter, *RCT* randomized controlled trial.

postoperative refractive astigmatism and a greater correction index compared to the FSAK group.

Secondary outcome

Three studies involving 222 eyes were included to compare postoperative uncorrected distance visual acuity (UDVA) between the two groups. A random effects model was utilized for the analysis due to significant heterogeneity. The mean difference in UDVA was 0.05 (95% CI = −0.01 to 0.11, $P = 0.09$, $I^2 = 70\%$). We found no statistically significant difference in UDVA between the two groups. However, a sensitivity analysis indicated that the TIOL group had better UDVA compared to the FSAK group after excluding one study[18] from the analysis (95% CI = 0.02 to 0.14, $P = 0.01$, $I^2 = 32\%$). The summary results are depicted in Fig. 4.

Sensitivity analysis and publication bias assessment

Figure 5 presents a summary of the outcomes of sensitivity analysis for all outcome measures. The sensitivity analysis revealed a stable result in the analysis about postoperative refractive astigmatism between the FSAK and TIOL groups, but unstable results about correction index and UDVA. For the correction index, the difference between the two groups became non-significant after omitting three articles [12, 16, 17] one by one. Conversely, the mean difference in UDVA was significant after omitting one study [18] from the analysis. Egger's test indicated no publication bias for included studies in the analyses of postoperative refractive astigmatism ($t = 1.10$, $P = 0.351$), correction index ($t = 0.46$, $P = 0.691$), and UDVA ($t = 2.23$, $P = 0.269$).

Discussion

To our knowledge, this is the first meta-analysis focused on the effect of FSAK and TIOL on astigmatism correction. The results showed that postoperative refractive astigmatism in the TIOL group was smaller than that in the FSAK group, indicating superior performance in astigmatism correction in the TIOL group. The greater correction index induced by TIOL implantation also supports this conclusion. Since the sensitivity analysis revealed unstable results of the analyses about correction index and UDVA, however, these results need to be interpreted cautiously. The number of included studies may be relevant to the sensitivity analysis outcomes. Four and three studies were included in the correction index and UDVA analyses, respectively. Owning to the limited number of included studies, excluding any one study may significantly influence the overall results. Additionally, varying degrees of preoperative corneal

Table 2 The details and primary outcomes of the included studies

Author/Y	FSAK				TIOL			Follow-up duration (month)	Femtosecond laser platform
	IOL	Details of FSAK	Postoperative refractive astigmatism (D)	Correction index	IOL	Postoperative refractive astigmatism (D)	Correction index		
Hernandez 2022	Eye-CEE One	Incision depth: 80% depth corneal local pachymetry guided by OCT; the optical zone diameter: 8.5 mm	-0.90 ± 0.53	0.95 ± 0.30	TECNIS Toric ZCT	-0.63 ± 0.55	1.06 ± 0.21	6	Technolas Victus
Kwon 2021	ZCB00 or PCB00	Incision depth: Central 60% of total corneal thickness remaining upper 20% and lower 20%; the optical zone diameter: 8.0 mm	0.99 ± 0.51	0.78 ± 0.43	TECNIS Toric	0.68 ± 0.21	0.78 ± 0.32	6	Catalys
Lin 2021	TECNIS	Incision depth: From 100 µm above the endothelium to the surface of the epithelium; the optical zone diameter: 8.0 mm	-0.98 ± 0.61	0.87 ± 0.60	T-flex Toric	-0.92 ± 0.72	0.97 ± 0.37	6	LENSAR
Noh 2021	Acrysof IQ	Incision depth: 85% of total corneal thickness; the optical zone diameter: 9.0 mm	-0.80 ± 0.73	0.71 ± 0.60	IQ Toric	-0.46 ± 0.32	0.84 ± 0.39	12	LenSx
Wang 2022	LS-313MF30	Incision depth: 90% of total corneal thickness; the optical zone diameter: 9.0 mm	0. 417 ± 0. 183	NA	LS-313MF30T	0. 260 ± 0. 132	NA	3	NA

FSAK femtosecond laser-assisted arcuate keratotomy, *TIOL* toric intraocular lens, *D* diopter.

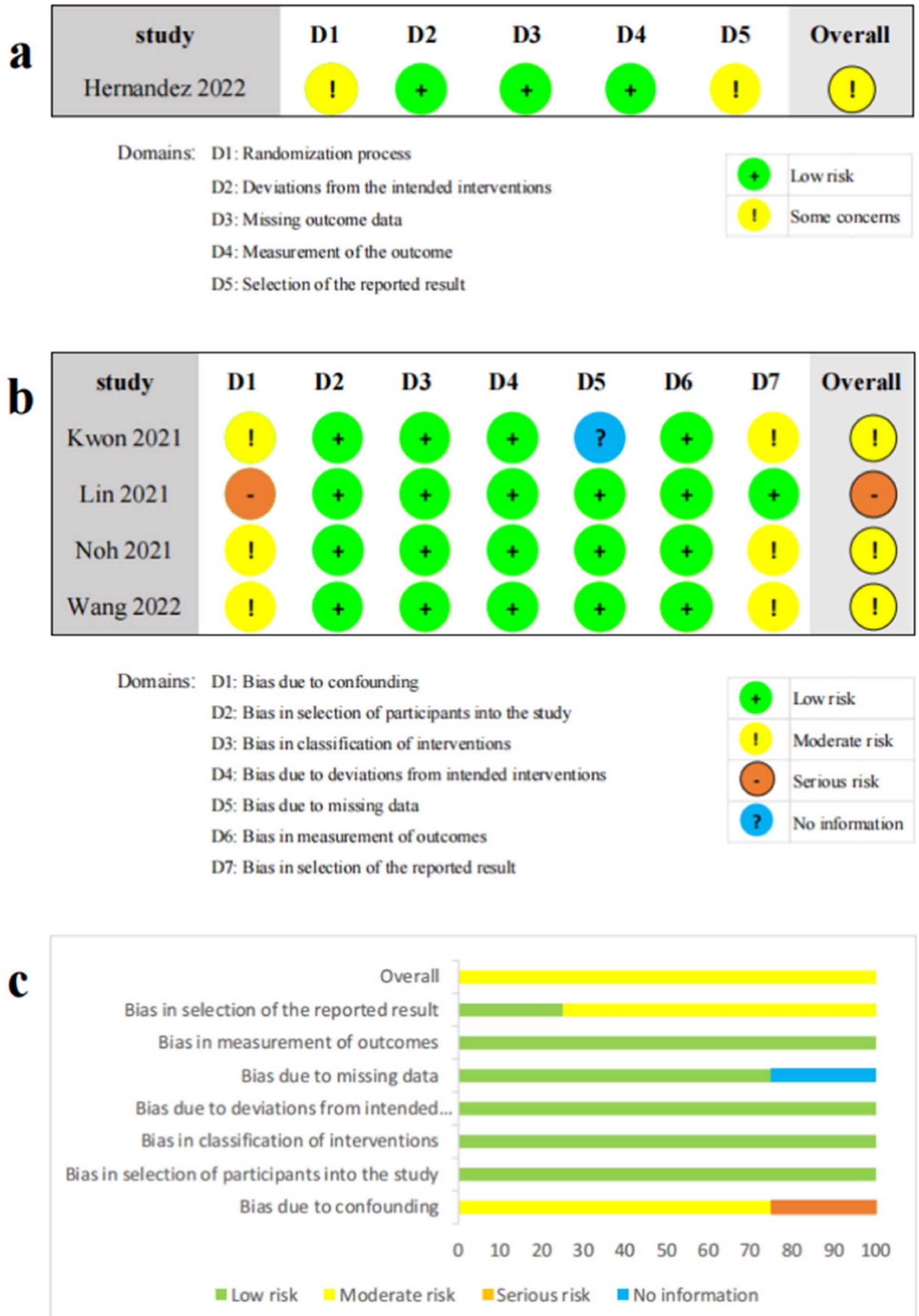


Fig. 2 Risks of bias assessment. **a** Risk of bias summary of randomized controlled trial; **b** risk of bias summary of non-randomized comparative studies; **c** risk of bias graph of non-randomized comparative studies

refractive wastigmatismwin participants possibly contribute to the instability of the results in the two analyses. The correction index is determined by calculating the ratio of SIA to TIA. A reduced level of corneal refractive astigmatism before surgery leads to a diminished degree of TIA. Although our results showed a discrepancy in the capacity to correct astigmatism between FSAK and TIOL implantation, this difference may diminish if the TIA is minimal. The three studies [12, 16, 17] that influenced the outcome of the correction index analysis involved patients with higher preoperative corneal refractive astigmatism or TIA. Omitting any of these studies could potentially alter the discrepancy in the correction index from being statistically significant to non-significant. In the analysis of UDVA, the investigation carried out by Wang et al. [18] included patients with low preoperative corneal astigmatism (< 1.00D). Consequently, postoperative residual astigmatism was not severe in this study, potentially resulting in an insignificant difference in

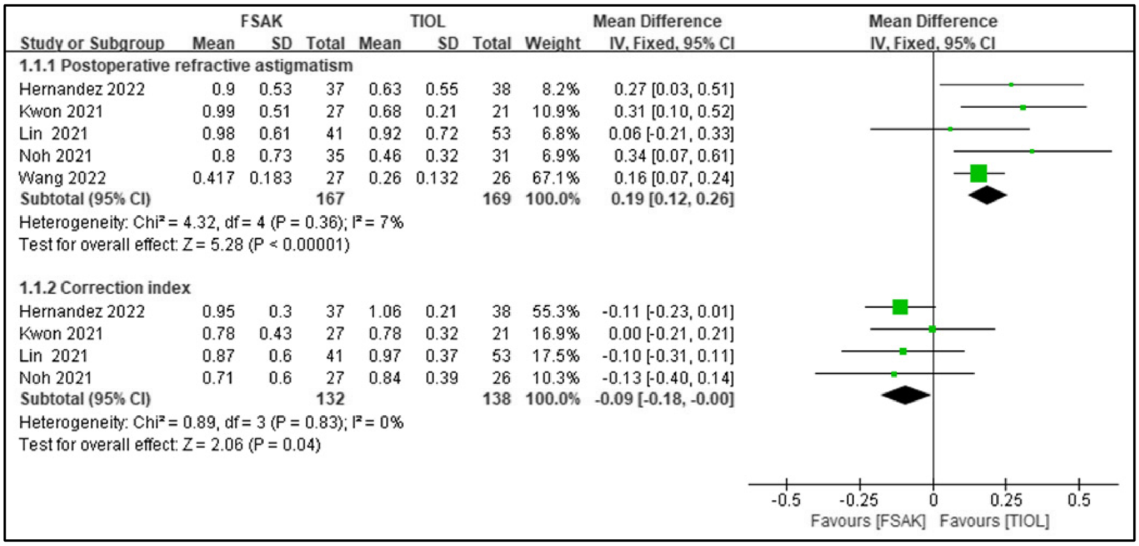


Fig. 3 Forest plot for meta-analysis of postoperative refractive astigmatism and correction index between femtosecond laser-assisted arcuate keratotomy (FSAK) and toric intraocular lens (TIOL) implantation

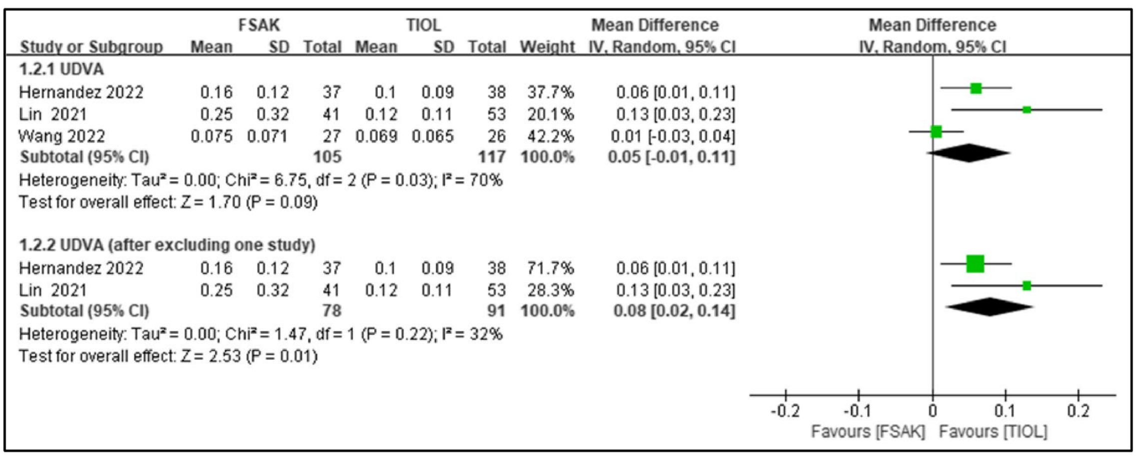


Fig. 4 Forest plot for meta-analysis of uncorrected distance visual acuity (UDVA) between femtosecond laser-assisted arcuate keratotomy (FSAK) and toric intraocular lens (TIOL) implantation

postoperative UDVA between the two groups. However, the other two studies [12, 16] included in UDVA analysis involved patients with larger corneal astigmatism. Thus, the difference in UDVA may become apparent when the study conducted by Wang et al. is omitted. Additionally, in the analysis of secondary outcome, heterogeneity may arise from different research methods and preoperative astigmatism levels. However, we do not have enough studies to conduct subgroup analysis or meta-regression to identify specific sources of significant heterogeneity.

Previous studies have shown that corneal incisions heal and the correction effect of astigmatism remains stable at 3 months after cataract surgery [1, 19]. In the present meta-analysis, all of the included studies had a minimum follow-up duration of 3 months. A retrospective study conducted by Yoo et al. [11] revealed that the amount of residual astigmatism was comparable between FSAK and TIOL procedures, while the correction index was higher in FSAK than in TIOL implantation. This study was not included in the meta-analysis because its FSAK was performed on patients more than one month after cataract surgery. Corneal incisions made during cataract surgery can cause corneal astigmatism [20–22]. In the study by Yoo et al. [11], patients in the FSAK group may have had preoperative astigmatism

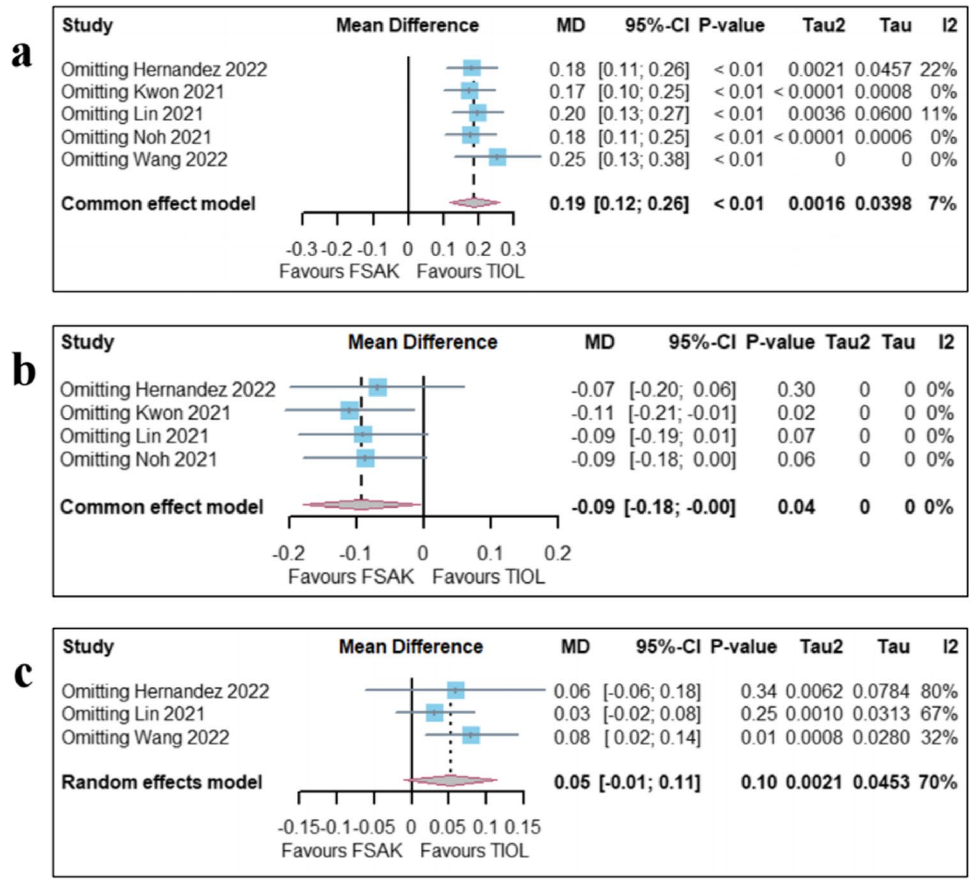


Fig. 5 Sensitivity analysis outcomes for the analyses of postoperative refractive astigmatism (**a**), correction index (**b**), and uncorrected distance visual acuity (**c**)

caused by cataract surgery incisions. As the corneal incision heals, this astigmatism may decrease, but it is not due to the correction effect of FSAK. Therefore, the astigmatism correction ability of FSAK in this study may be overestimated, which may be the reason for its results being different from those of the present meta-analysis. To eliminate the impact of varying time intervals after phacoemulsification on residual astigmatism and correction index outcomes, FSAK and phacoemulsification should be performed as a single procedure. Additionally, a prospective cohort study from China compared three surgical methods for correcting low corneal astigmatism during cataract surgery, including TIOL implantation, FSAK, and manual corneal relaxing incisions. It was found that the residual astigmatism in the TIOL group was smaller than that in the FSAK group, and the largest in the manual corneal relaxing incision group. Compared to the other two groups, the FSAK group had lower higher-order aberrations and better visual quality [23]. Due to issues with the measurement of residual astigmatism, we were unable to obtain useful data from this literature and did not include it in the meta-analysis.

In conclusion, it seems that TIOL implantation is superior to FSAK combined non-toric IOL implantation in correcting pre-existing corneal astigmatism in cataract patients. Several studies have demonstrated that FSAK is effective in correcting low to moderate astigmatism, with the amount of correction typically ranging from 0.50D to 1.50D [24–28]. Noh et al. [17] divided patients into two groups based on their TIA (TIA < 1.50D and TIA ≥ 1.50D) to compare the effectiveness of FSAK and TIOL implantation in correcting astigmatism. They found that the difference in residual astigmatism and correction index was only statistically significant in the group with a high degree of TIA. It can be inferred that the corrective advantage of TIOL implantation may diminish as the degree of preoperative corneal astigmatism decreases. Regrettably, the number of studies available was insufficient to perform a subgroup analysis based on the degree of preoperative corneal refractive astigmatism to substantiate this supposition.

Although our findings indicate that FSAK is less effective than TIOL implantation in correcting corneal astigmatism in cataract patients, it remains a viable alternative for those undergoing femtosecond laser-assisted cataract surgery (FLACS) who are not suitable for TIOL implantation due to eye conditions or not willing to receive TIOL implantation. Particularly for the management of low corneal astigmatism (< 1.50 D), FSAK can be generally utilized during FLACS [7]. In addition to effectively correcting low astigmatism, the results of FSAK correction also demonstrate long-term stability [29]. For pre-existing moderate to high corneal astigmatism, TIOL implantation is a superior method of control compared to FSAK. Further studies should focus more on the difference between FSAK and TIOL implantation in correcting different degrees of astigmatism, which may provide accurate guidance for the clinical application of FSAK.

Limitations

This meta-analysis is subject to several limitations. Firstly, the degrees of preoperative corneal astigmatism of the studies included in the meta-analysis were not entirely consistent, which might cause considerable heterogeneity. Secondly, most of the studies included in the present meta-analysis were of a non-randomized design. Quality assessments showed that the included studies were at low risk in most domains and no study had a critical risk of overall bias, which can support the credibility of the evidence to a certain extent. Lastly, insufficient research made it unsuitable to perform a subgroup analysis according to preoperative corneal refractive astigmatism to reveal the difference between FSAK and TIOL implantation in correcting different degrees of astigmatism. The impacts of these limitations on the conclusion of the present meta-analysis may be minimized by developing a comprehensive and detailed protocol, conducting a thorough literature search and appropriate study selection process, and employing explicit methods for data extraction and analysis.

Conclusions

FSAK was found to be less effective than TIOL in correcting preoperative corneal astigmatism in cataract patients. Patients who received TIOL implantation had lower residual astigmatism and a higher correction index than those who underwent FSAK combined with non-toric IOL implantation. The two methods seemed not to differ in their effect on postoperative UDVA. Due to the outcomes of the sensitivity analysis, the results of the correction index and UDVA analyses should be interpreted with caution. Further research is necessary to determine whether the difference in correction effect between the two surgical methods may vary when refined to different preoperative astigmatism levels. TIOL implantation is the preferred method for correcting preoperative corneal astigmatism in cataract patients. FSAK can be used for those with corneal astigmatism who do not wish to receive TIOL implantation or are not suitable for TIOL implantation due to eye conditions. Additionally, considering its effectiveness, precision, and safety, FSAK may be a suitable option for managing low corneal astigmatism in FLACS.

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Author contribution Conceptualization; literature search and data extraction; risk of bias assessment; statistical analysis; writing—original draft preparation; writing—reviewing and editing: Jiang Zheng and Lun He; conceptualization, supervision: Jingxiang Zhong. All authors have contributed significantly.

Data availability All data relevant to the study are included in the article.

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval Not applicable.

Consent for publication Not applicable.

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