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Hans汉斯

飞秒激光小切口角膜基质透镜取出术矫正近视散光影响因素的研究进展

邓玉洁[*]，**王 铮**[#]

暨南大学附属爱尔眼科医院，广东 广州

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摘 要

飞秒激光小切口角膜基质透镜取出术(Small incision lenticule extraction, SMILE)凭借微创、无瓣和高精准度的特点，受到越来越多近视患者的青睐。研究表明，SMILE手术在矫正近视及近视散光方面具有较好的安全性、有效性、稳定性和可预测性，并且术后能够获得较好的视觉质量。然而，现有研究指出SMILE在矫正近视散光方面总体上存在欠矫趋势，影响SMILE矫正散光的因素包括术前散光大小、散光轴位、角膜上皮重塑、术中眼球旋转、眼内散光等因素。本文就SMILE在矫正近视散光中的影响因素以及现有补偿措施方法进行综述。

关键词

飞秒激光小切口角膜基质透镜取出术，近视散光，角膜屈光手术

Research Progress on Influencing Factors of Myopic Astigmatism Correction with Small Incision Lenticule Extraction

Yujie Deng[*], **Zheng Wang**[#]

Aier Eye Hospital, Jinan University, Guangzhou Guangdong

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Abstract

Small incision lenticule extraction (SMILE) has gained increasing popularity among myopic patients

[*]第一作者。
[#]通讯作者。

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due to its minimally invasive, flapless, and high-precision features. Studies have demonstrated that SMILE exhibits favorable safety, efficacy, stability, and predictability in correcting myopia and myopic astigmatism, with satisfactory postoperative visual quality. However, current evidence indicates a general trend of undercorrection in astigmatism treatment with SMILE. Key influencing factors include preoperative astigmatism magnitude, astigmatic axis, corneal epithelial remodeling, intraoperative cyclorotation, and ocular residual astigmatism (ORA) among others. This review systematically summarizes the critical factors affecting astigmatism correction accuracy in SMILE and discusses existing compensatory strategies.

Keywords

Small Incision Lenticule Extraction, Myopic Astigmatism, Corneal Refractive Surgery

1. 引言

2011 年，飞秒激光小切口角膜基质透镜取出术(Small incision lenticule extraction, SMILE)问世，标志着屈光手术走向更准、更快、更安全的新境界。凭借微创、无瓣和高精准度的特点，SMILE 手术逐渐成为众多近视患者的首选[1]-[3]。该术式通过飞秒激光在角膜基质层间进行两次扫描制作角膜透镜，并通过 2 mm 侧切口将透镜取出，最大程度保留了角膜前表面的完整性。理论上，此术式更好维持了角膜生物力学性能，避免了角膜瓣相关并发症，且能在一定程度上减少术后干眼的发生[4]-[6]。大量研究表明，SMILE 手术在矫正近视及近视散光方面具有较好的安全性、有效性、稳定性和可预测性，并且术后能够获得较好的视觉质量[7]-[9]。然而，现有研究指出 SMILE 在矫正近视散光方面总体上存在欠矫趋势，SMILE 对散光矫治的准确性受到诸多因素的影响，如术前散光度数及轴位、角膜上皮重塑、术中眼球旋转、眼内散光等。如何提高 SMILE 矫正近视散光的精确性目前已成为手术医生的研究热点。

2. 影响因素

2.1. 术前散光大小

在人群中，36.2%的患者散光 ≥1.00 D [10]，而散光的术后矫正效果与视觉质量密切相关。报告显示，SMILE 矫正中度至高度散光存在欠矫[11]-[14]，且随着预期矫正散光度数的增加，欠矫的趋势也随之上升[11] [13] [15] [16]。Ivarsen 和 Hjordtal [10]首次通过散光矢量分析法评估了 SMILE 矫正近视散光的术后结果，发现低散光组(≤2.25 D)术后平均欠矫 0.17 D (欠矫率 13%)，而高散光组(>2.25 D)术后平均欠矫 0.59 D (欠矫率 16%)。Pedersen 等学者[11]的研究显示，SMILE 矫正近视散光一年后仍有 11%的欠矫。王雁团队[13]为期一年的前瞻性观察研究指出，术前散光度数低于 0.50 D 的患者常表现为术后过矫，而随着散光度数的增加，矫正效果逐渐呈现欠矫。Qian 等学者[17]的研究也支持这一结论，认为低度散光的验光轴位误差较高度散光大，轴位误差可能是导致低度散光过矫的主要因素。在散光度数方面，SMILE 在散光矫正上的主要趋势为欠矫，且术前散光度数越大，矫正精准性也越差，欠矫趋势愈为明显。目前，国际上推荐对散光进行经验性的 10%加量调整[11] [14] [18]，但对术前散光度数调整的具体方法尚未达成统一共识。

2.2. 散光轴向

目前，关于散光类型是否影响 SMILE 术后结果仍存在争议。Hjortdal and Ivarsen 等学者[19]在一项大样本(n = 829)的回顾性研究中对比了 SMILE 矫正逆规和顺规散光术后 3 个月的临床效果，发现两组散光平均每 1 D 欠矫 0.15 D，且逆规散光相较顺规散光有 0.32 D 的恒定过矫。随着散光度数的增加，逆规散光显示从过矫到欠矫的过渡，而顺规散光则呈现出固定的欠矫趋势。因此，Ivarsen 等学者[19]建议应根据散光轴向对目标矫正散光度数进行相应调整。Pérez-Izquierdo 等学者[20]发现当散光 ≥ 1.50 D 时，顺规散光的误差幅度绝对值明显大于逆规和斜轴散光，建议对顺规散光进行 13%的加量调整。然而，Igras 等学者[21]的研究表明，逆规散光术后残余散光和等效球镜(Spherical equivalent, SE)均低于顺规和斜轴散光，但这可能与术前三组散光的屈光状态不匹配有关——逆规散光组术前散光和球镜度数较低。由于散光类型在人群中的发病率存在差异，相关研究在样本量和术前散光度数上可能存在一定偏倚，使得难以对不同类型散光的矫正效果进行有效对比。然而，大部分研究都表明顺规散光相比逆规或斜轴散光更容易欠矫，且较高的顺规散光度数与欠矫量增加相关[16] [19] [20]。

2.3. 角膜上皮重塑

散光的过矫或欠矫可能与术后角膜上皮重塑有关。Yu 等学者[22]指出 SMILE 矫正散光 ≥ 2.00 D 术后可伴有明显的平轴上的对称性上皮增厚，且平轴和陡轴的上皮厚度差异与术后残余散光度显著正相关($r = -0.334$, $p = 0.035$)，提示术后上皮的补偿效应可能是导致不同类型散光矫正效果差异的重要因素。同样，Brunner 等学者[23]在 SMILE 矫正近视散光术后 3 月也观察到了平轴上的上皮重塑较陡轴更为显著。SMILE 矫正近视散光所制作的屈光透镜，其散光的矫正是通过减少散光陡轴的透镜厚度得以矫正，在逆规散光中，角膜形态改变在垂直子午线上更为显著，表现为其周边区域提取的基质透镜厚度最大，进而该区域的术后角膜上皮重塑也更为活跃。由此可见，角膜上皮的补偿效应可能削弱不同轴向散光矫正效果，进而导致术后过矫和欠矫的发生。未来的研究应进一步分析不同类型散光术后上皮重塑的差异，以及上皮重塑与术后屈光结果之间的关系。

2.4. 眼球旋转

由于缺乏准分子激光系统所配备的虹膜识别和主动眼球追踪系统，SMILE 术中的切削中心定位主要依赖于患者的主观固视和手术医生的操作[24]。Ganesh 等[25]报道约 82%的患者从坐立位变为平卧位时会发生眼球旋转，其中 20%的患者的旋转角度超过 5˚。理论上，眼球的旋转会导致散光欠矫概率的增大，4˚旋转将导致散光矫正率损失 14%，6˚旋转损失 20%，而 30˚旋转则损失一半[26]。可见散光轴的定位对术后效果有着至关重要的影响。

2.5. 眼内散光

全眼散光的构成主要包括角膜前表面散光和眼内散光(Ocular residual astigmatism, ORA)，后者是指在角膜平面计算的屈光性散光和角膜前表面散光的矢量差[27] [28]。ORA 代表眼内所有散光源的总和，包括角膜后表面、晶状体、玻璃体、视网膜倾斜和非光学皮质感知等因素。Frings 等学者[29]在 2991 例患者中发现平均 ORA 为 0.73 D，其中 46%的患者 ORA 超过 1.00 D。Wallerstein 等学者[30]在其研究中对 21,581 眼的术前 ORA 进行了详尽的分析，指出 ORA 在人群中呈偏态分布，平均值为 0.73 D。可见 ORA 是全眼散光的重要组成成分。Qian 等[31]、Chan 等[32]和卢等学者[33]的研究一致发现较高的 ORA 会导致术后更高的残余散光。Jun 等学者[34]建议治疗高 ORA 病例时，应用矢量规划法可以降低术后残余散光。但关于这方面的研究相对欠缺，需要更多的研究证实 ORA 对 SMILE 矫正近视散光的影响机制。

3. 误差控制

Zhang 等学者[13] [24]的研究表明，目标矫正散光(Target induced astigmatism, TIA)与矫正指数(Correction index, CI)显著负相关($r = -0.461$, $p < 0.001$)，而成功指数(Index of success, IOS)与 AE 的绝对值显著正相关($r = 0.938$, $p < 0.001$)。这些结果提示，SMILE 散光矫正的不足主要归因于未使用特定的 nomogram 以及术中眼球旋转引起的轴位误差。因此，本文接下来将集中讨论如何控制这两个关键因素的误差。

3.1. 人工角膜缘标记

Ganesh 等学者[25]建议增加 10%的散光矫正量，并在术前标记角膜缘水平轴，以便在术中进行手动旋转补偿。他们的研究发现高散光组(>1.50 D)AE 和 IOS 较低散光组(0.75 D~1.50 D)更低，但高散光组术后散光和 CI 分别为−0.31 D 和 0.93，表示仍存在 7%的欠矫。Jun 等学者[35]比较了 SMILE 手术(采用三重标记中心定位技术)和波前像差引导的准分子激光角膜切削术(Photorefractive keratectomy, PRK)矫正高度近视散光(≥2.50 D)的术后效果，发现角膜缘标记对轴位有修正作用，但 SMILE 组对散光矫正效果仍不及 PRK 组。Kang 等学者[36]进一步证明该方法不仅能减少光学区偏心，还能降低高阶像差、球差及彗差的引入。然而，人工角膜缘标记存在主观因素的干扰，标记误差范围为 3.77˚~6.01˚，存在标记模糊、错位和影响激光扫描等潜在风险。也有研究认为手动旋转补偿并不是 SMILE 手术矫正近视散光的必需步骤[37]。Xu 等学者[38]的研究发现，眼球平均旋转角度较小(3.21˚ ± 2.33˚)，并且对照组和手动旋转补偿组在矫正近视散光方面具有可比的结果，可不对眼球进行旋转补偿。Chuckpaiwong 等学者[39]对行 SMILE 手术的 5953 例眼进行了为期 1 年的随访，发现在严格的体位和头位控制下，未进行手动旋转补偿的患眼术后仍具有较好的安全性、可预测性和稳定性，但该研究缺少对照组。总之，虽然研究证明角膜缘标记法在散光矫正中具有一定的有效性，但目前对于人工角膜缘标记法在 SMILE 手术中的应用仍缺乏统一的标准和共识。

3.2. Nomogram

在临床工作中，由于不同屈光中心手术设备的细微差异，手术环境(温度、湿度和空气流速)不同，手术医生学习曲线差异等影响，预计的屈光矫正度数和实际的屈光矫正度数可能存在一定的偏差，而较大的偏差可能会引起术后明显的过矫或欠矫，导致术后视觉质量的下降。Nomogram，也称为“诺莫图”或“列线图”，是一种通过统计回归分析术前屈光度数与术后屈光度数之间关系的模型，旨在预测术前所需的屈光矫正量，从而实现更精准的矫正效果[40] [41]。以往研究发现，术前显然验光度数、年龄、角膜生物力学参数、调节反应、角膜曲率等影响因素可作为 nomogram 设计值的预测参数[42]-[46]。在原位角膜磨镶嵌术(Lase *in situ* keratomileusis, LASIK)以及其他准分子角膜屈光手术领域，nomogram 已被广泛验证能够提高矫正 SE 和散光的精确性[47]-[51]。各种类型的准分子设备已经具有比较精准的 nomogram 体系，但在 SMILE 的术前设计中，传统的 nomogram 的调整仍主要依赖于手术医生的个人经验，且多侧重于矫正球镜或 SE 误差上。例如，以往文献大多对球镜进行 5%~10%的经验性加量[44] [52]-[54]，针对 SMILE 矫正散光普遍存在的欠矫问题，国际上认为 10%的加量调整是较为科学的[11] [18]。

临床上常用简单线性回归或多元线性回归的方法，纳入两个和两个以上的变量建立 nomogram 预测模型。Liang 等学者[42]首先纳入术前 SE、年龄、角膜厚度等影响因素进行多变量分析，发现术前 SE 与 SE 矫正误差有明显的相关性，再借助简单线性回归法基于 SE 矫正误差建立 nomogram。Yu 等学者[52]则基于 TIA 与平坦效应(Flattening effect, FE)之间的线性回归关系，建立了散光 nomogram。此方法可理解为基于拟矫量与实矫量的简单线性回归法，FE 代表手术矫正散光量(Surgically induced astigmatism, SIA)在 TIA 轴向上的效应，即 $FE = SIA \times \cos(2AE)$，由于误差角度(Angle of error, AE)非常小(1.2˚ ± 1.7˚)，

因此可以忽略不计，FE 代替了 SIA。这两项研究均证实 nomogram 的应用显著提高了 SMILE 术后的可预测性。

此外，散光 nomogram 的其他建立方法还包括 Alpins 方法[55]，Thibos 方法[56] [57]和矢量规划法[34] [58]。Alpins 方法基于样本均数计算散光调整系数(Coefficient of adjustment, CA)，其公式为 CA = TIA/SIA，例如，当 CA 值为 1.10 时，表示需要对散光进行 10%过矫。Thibos 矢量方法将散光分解到 J0 和 J45 两个部分，分别进行拟矫量与实矫量的线性回归，再结合成新的散光矢量。矢量规划则建议在高 ORA 眼中，60%治疗重点分配于屈光性散光，40%于角膜散光。这些方法各有优缺点。例如，TIA 与 SIA 的线性回归法计算简单且能够精准量化调整值，但忽略了轴位旋转对散光矫正的影响。Alpins 方法是一种平均补偿策略，这是一种简化的调整方法。Thibos 矢量分析法考虑了散光的轴位旋转，但其计算繁杂，不易于临床广泛应用。矢量规划法在低 ORA 眼中不适用，且目前关于矢量规划法在 SMILE 矫正散光的研究中仍然较少。目前，nomogram 的调整多聚焦于单一屈光成分的优化，缺乏球柱镜联合调整的数学框架；其次，在已有加量调整的基础上如何更新下一次的输机矫正量公式，也是一个亟待解决的问题；最为重要的是，散光 nomogram 的应用较为有限。

3.3. VisuMAx 800

第二代全飞秒激光设备 VisuMax 800 的问世推动了屈光手术的革新。其飞秒激光脉冲频率 2000 kHz 是 VisuMax 500 的四倍，能将 SMILE 手术中微透镜的扫描时间从 23 秒缩短至 10 秒。此外，VisuMax 800 还引入了智能辅助系统，包括眼球旋转补偿和精确的中心定位功能，从而显著提升了手术的精确度与安全性。在 Ganesh 等学者[59]的研究中，对患者一眼使用 VisuMax 800 而另一眼使用 VisuMax 500 进行手术的对比分析显示，两种设备的术后早期效果相当，但 VisuMax 800 的手术时间更短，患者满意度更高。另有研究指出，得益于其半自动化的眼球旋转补偿技术，VisuMax 800 在矫正散光方面的精确性得到了提升[60] [61]。

4. 总结

SMILE 在矫正近视散光尤其是高度散光方面仍面临诸多挑战。为提高矫正散光的精确性，研究者们提出了多种补偿策略，如人工角膜缘标记、nomogram 调整以及应用最新一代的 VisuMax 800 设备。现有研究表明，新的方法、新的技术以及术者经验的提升能对散光矫正不足进行有效修正，但仍需更多研究来优化 SMILE 手术的散光矫正的精确性和可预测性，尤其是在不同散光类型、术后上皮重塑、nomogram 的建立和应用等方面。未来的研究应聚焦于 VisuMax 800 联合 nomogram 调整在近视散光治疗中的效果，以期为临床实践提供更为精准和有效的指导。

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参考文献

[1] Taneri, S., Knepper, J., Rost, A. and Dick, H.B. (2021) PRK, LASIK, SMILE im Langzeitverlauf. *Der Ophthalmologe*, **119**, 163-169. https://doi.org/10.1007/s00347-021-01449-7

[2] Ivarsen, A., Asp, S. and Hjortdal, J. (2014) Safety and Complications of More than 1500 Small-Incision Lenticule Extraction Procedures. *Ophthalmology*, **121**, 822-828. https://doi.org/10.1016/j.ophtha.2013.11.006

[3] Vestergaard, A., Ivarsen, A.R., Asp, S. and Hjortdal, J.Ø. (2012) Small-Incision Lenticule Extraction for Moderate to High Myopia: Predictability, Safety, and Patient Satisfaction. *Journal of Cataract and Refractive Surgery*, **38**, 2003-2010. https://doi.org/10.1016/j.jcrs.2012.07.021

[4] Luft, N., Schumann, R.G., Dirisamer, M., Kook, D., Siedlecki, J., Wertheimer, C., *et al*. (2018) Wound Healing, Inflammation, and Corneal Ultrastructure after SMILE and Femtosecond Laser-Assisted LASIK: A Human *ex Vivo* Study. *Journal of Refractive Surgery*, **34**, 393-399. https://doi.org/10.3928/1081597x-20180425-02

[5] Wu, D., Wang, Y., Zhang, L., Wei, S. and Tang, X. (2014) Corneal Biomechanical Effects: Small-Incision Lenticule Extraction versus Femtosecond Laser-Assisted Laser *in Situ* Keratomileusis. *Journal of Cataract and Refractive Surgery*, **40**, 954-962. https://doi.org/10.1016/j.jcrs.2013.07.056

[6] Kobashi, H., Kamiya, K. and Shimizu, K. (2017) Dry Eye after Small Incision Lenticule Extraction and Femtosecond Laser-Assisted Lasik: Meta-Analysis. *Cornea*, **36**, 85-91. https://doi.org/10.1097/ico.0000000000000999

[7] Liu, M., Chen, Y., Wang, D., Zhou, Y., Zhang, X., He, J., *et al*. (2016) Clinical Outcomes after SMILE and Femtosecond Laser-Assisted LASIK for Myopia and Myopic Astigmatism: A Prospective Randomized Comparative Study. *Cornea*, **35**, 210-216. https://doi.org/10.1097/ico.0000000000000707

[8] Lin, F., Xu, Y. and Yang, Y. (2014) Comparison of the Visual Results after SMILE and Femtosecond Laser-Assisted LASIK for Myopia. *Journal of Refractive Surgery*, **30**, 248-254. https://doi.org/10.3928/1081597x-20140320-03

[9] Sekundo, W., Gertnere, J., Bertelmann, T. and Solomatin, I. (2014) One-Year Refractive Results, Contrast Sensitivity, High-Order Aberrations and Complications after Myopic Small-Incision Lenticule Extraction (ReLEx SMILE). *Graefe's Archive for Clinical and Experimental Ophthalmology*, **252**, 837-843. https://doi.org/10.1007/s00417-014-2608-4

[10] Vitale, S., *et al*. (2008) Prevalence of Refractive Error in the United States, 1999-2004. *Archives of Ophthalmology*, **126**, 1111-1119. https://doi.org/10.1001/archopht.126.8.1111

[11] Pedersen, I.B., Ivarsen, A. and Hjortdal, J. (2017) Changes in Astigmatism, Densitometry, and Aberrations after SMILE for Low to High Myopic Astigmatism: A 12-Month Prospective Study. *Journal of Refractive Surgery*, **33**, 11-17. https://doi.org/10.3928/1081597x-20161006-04

[12] Chan, T.C.Y., Ng, A.L.K., Cheng, G.P.M., Wang, Z., Ye, C., Woo, V.C.P., *et al*. (2015) Vector Analysis of Astigmatic Correction after Small-Incision Lenticule Extraction and Femtosecond-Assisted LASIK for Low to Moderate Myopic Astigmatism. *British Journal of Ophthalmology*, **100**, 553-559. https://doi.org/10.1136/bjophthalmol-2015-307238

[13] Zhang, J., Wang, Y., Wu, W., Xu, L., Li, X. and Dou, R. (2015) Vector Analysis of Low to Moderate Astigmatism with Small Incision Lenticule Extraction (SMILE): Results of a 1-Year Follow-Up. *BMC Ophthalmology*, **15**, Article No. 8. https://doi.org/10.1186/1471-2415-15-8

[14] Ivarsen, A. and Hjortdal, J. (2014) Correction of Myopic Astigmatism with Small Incision Lenticule Extraction. *Journal of Refractive Surgery*, **30**, 240-247. https://doi.org/10.3928/1081597x-20140320-02

[15] Khalifa, M.A., Ghoneim, A.M., Shaheen, M.S. and Piñero, D.P. (2017) Vector Analysis of Astigmatic Changes after Small-Incision Lenticule Extraction and Wavefront-Guided Laser *in Situ* Keratomileusis. *Journal of Cataract and Refractive Surgery*, **43**, 819-824. https://doi.org/10.1016/j.jcrs.2017.03.033

[16] Moshirfar, M., Thomson, A.C., West Jr, W.B., Hall, M.N., McCabe, S.E., Thomson, R.J., *et al*. (2020) Initial Single-Site Experience Using SMILE for the Treatment of Astigmatism in Myopic Eyes and Comparison of Astigmatic Outcomes with Existing Literature. *Clinical Ophthalmology*, **14**, 3551-3562. https://doi.org/10.2147/opth.s276899

[17] Qian, Y., Huang, J., Zhou, X. and Wang, Y. (2015) Comparison of Femtosecond Laser Small-Incision Lenticule Extraction and Laser-Assisted Subepithelial Keratectomy to Correct Myopic Astigmatism. *Journal of Cataract and Refractive Surgery*, **41**, 2476-2486. https://doi.org/10.1016/j.jcrs.2015.05.043

[18] Alió del Barrio, J.L., Vargas, V., Al-Shymali, O. and Alió, J.L. (2017) Small Incision Lenticule Extraction (SMILE) in the Correction of Myopic Astigmatism: Outcomes and Limitations—An Update. *Eye and Vision*, **4**, Article No. 26. https://doi.org/10.1186/s40662-017-0091-9

[19] Ivarsen, A., Gyldenkerne, A. and Hjortdal, J. (2018) Correction of Astigmatism with Small-Incision Lenticule Extraction: Impact of Against-the-Rule and With-the-Rule Astigmatism. *Journal of Cataract and Refractive Surgery*, **44**, 1066-1072. https://doi.org/10.1016/j.jcrs.2018.06.029

[20] Pérez-Izquierdo, R., Rodríguez-Vallejo, M., Matamoros, A., Martínez, J., Garzón, N., Poyales, F., *et al*. (2019) Influence of Preoperative Astigmatism Type and Magnitude on the Effectiveness of SMILE Correction. *Journal of Refractive Surgery*, **35**, 40-47. https://doi.org/10.3928/1081597x-20181127-01

[21] Igras, E., Czarnota-Nowakowska, B. and O'Caoimh, R. (2023) Comparison of the Clinical Effectiveness of Correcting Different Types of Astigmatism with Small Incision Lenticule Extraction. *Journal of Clinical Medicine*, **12**, Article No. 6941. https://doi.org/10.3390/jcm12216941

[22] Yu, N., Ye, Y., Chen, P., Yang, Y., Zhuang, J. and Yu, K. (2021) Corneal Epithelial Thickness Changes Following SMILE for Myopia with High Astigmatism. *Journal of Refractive Surgery*, **37**, 224-230. https://doi.org/10.3928/1081597x-20210126-01

[23] Brunner, B.S., Feldhaus, L., Mayer, W.J., Siedlecki, J., Dirisamer, M., Priglinger, S.G., *et al*. (2024) Epithelial Remodeling and Epithelial Wavefront Aberrometry after Spherical vs. Cylindrical Myopic Small Incision Lenticule Extraction

(SMILE). *Journal of Clinical Medicine*, **13**, Article No. 3970. https://doi.org/10.3390/jcm13133970

[24] Zhang, J., Wang, Y. and Chen, X. (2016) Comparison of Moderate- to High-Astigmatism Corrections Using Wavefront-Guided Laser *in Situ* Keratomileusis and Small-Incision Lenticule Extraction. *Cornea*, **35**, 523-530. https://doi.org/10.1097/ico.0000000000000782

[25] Ganesh, S., Brar, S. and Pawar, A. (2017) Results of Intraoperative Manual Cyclotorsion Compensation for Myopic Astigmatism in Patients Undergoing Small Incision Lenticule Extraction (SMILE). *Journal of Refractive Surgery*, **33**, 506-512. https://doi.org/10.3928/1081597x-20170328-01

[26] Alpins, N.A. (1997) Vector Analysis of Astigmatism Changes by Flattening, Steepening, and Torque. *Journal of Cataract and Refractive Surgery*, **23**, 1503-1514. https://doi.org/10.1016/s0886-3350(97)80021-1

[27] Kugler, L., Crews, J. and Morgan, L. (2014) Ocular Residual Astigmatism. Researcher's Corner.

[28] Lin, J. (2021) The Contribution of Ocular Residual Astigmatism to Anterior Corneal Astigmatism in Refractive Astigmatism Eyes. *Scientific Reports*, **11**, Article No. 1018. https://doi.org/10.1038/s41598-020-80106-6

[29] Frings, A., Katz, T., Steinberg, J., Druchkiv, V., Richard, G. and Linke, S.J. (2014) Ocular Residual Astigmatism: Effects of Demographic and Ocular Parameters in Myopic Laser *in Situ* Keratomileusis. *Journal of Cataract and Refractive Surgery*, **40**, 232-238. https://doi.org/10.1016/j.jcrs.2013.11.015

[30] Wallerstein, A., Gauvin, M., Qi, S.R. and Cohen, M. (2020) Effect of the Vectorial Difference between Manifest Refractive Astigmatism and Anterior Corneal Astigmatism on Topography-Guided LASIK Outcomes. *Journal of Refractive Surgery*, **36**, 449-458. https://doi.org/10.3928/1081597x-20200609-01

[31] Qian, Y., Huang, J., Chu, R., Zhao, J., Li, M., Zhou, X., *et al*. (2015) Influence of Intraocular Astigmatism on the Correction of Myopic Astigmatism by Femtosecond Laser Small-Incision Lenticule Extraction. *Journal of Cataract and Refractive Surgery*, **41**, 1057-1064. https://doi.org/10.1016/j.jcrs.2014.09.036

[32] Chan, T.C.Y., Wan, K.H., Zhang, L. and Wang, Y. (2019) Impact of Ocular Residual Astigmatism on Predictability of Myopic Astigmatism Correction after Small-Incision Lenticule Extraction. *Journal of Cataract and Refractive Surgery*, **45**, 525-526. https://doi.org/10.1016/j.jcrs.2019.01.028

[33] 卢玥浩, 夏丽坤, 于泳, 等. 眼内散光对 SMILE 矫正近视散光术后视觉质量的影响[J]. 中华眼视光学与视觉科学杂志, 2020, 22(10): 728-737.

[34] Jun, I., Kang, D.S.Y., Arba-Mosquera, S., Reinstein, D.Z., Archer, T.J., Jean, S.K., *et al*. (2020) Comparison of Clinical Outcomes between Vector Planning and Manifest Refraction Planning in SMILE for Myopic Astigmatism. *Journal of Cataract and Refractive Surgery*, **46**, 1149-1158. https://doi.org/10.1097/j.jcrs.0000000000000100

[35] Jun, I., Kang, D.S.Y., Reinstein, D.Z., Arba-Mosquera, S., Archer, T.J., Seo, K.Y., *et al*. (2018) Clinical Outcomes of SMILE with a Triple Centration Technique and Corneal Wavefront-Guided Transepithelial PRK in High Astigmatism. *Journal of Refractive Surgery*, **34**, 156-163. https://doi.org/10.3928/1081597x-20180104-03

[36] Kang, D.S.Y., Lee, H., Reinstein, D.Z., Roberts, C.J., Arba-Mosquera, S., Archer, T.J., *et al*. (2018) Comparison of the Distribution of Lenticule Decentration Following SMILE by Subjective Patient Fixation or Triple Marking Centration. *Journal of Refractive Surgery*, **34**, 446-452. https://doi.org/10.3928/1081597x-20180517-02

[37] Lin, H., Fang, Y., Chuang, Y., Karlin, J.N., Chen, H., Lin, S., *et al*. (2017) A Comparison of Three Different Corneal Marking Methods Used to Determine Cyclotorsion in the Horizontal Meridian. *Clinical Ophthalmology*, **11**, 311-315. https://doi.org/10.2147/opth.s124580

[38] Xu, J., Liu, F., Liu, M., Yang, X., Weng, S., Lin, L., *et al*. (2019) Effect of Cyclotorsion Compensation with a Novel Technique in Small Incision Lenticule Extraction Surgery for the Correction of Myopic Astigmatism. *Journal of Refractive Surgery*, **35**, 301-308. https://doi.org/10.3928/1081597x-20190402-01

[39] Chuckpaiwong, V., Chansue, E., Lekhanont, K., Tanehsakdi, M., Jongkhajornpong, P. and Nonpassopon, M. (2023) 12-Month Outcomes of Small Incision Lenticule Extraction with Proper Head Positioning but No Reference Marking for the Correction of Astigmatism. *Journal of Refractive Surgery*, **39**, 683-692. https://doi.org/10.3928/1081597x-20230824-01

[40] Mrochen, M., Hafezi, F., Iseli, H.P., Löffler, J. and Seiler, T. (2006) Verbesserung der refraktiven Ergebnisse durch Nomogramme. *Der Ophthalmologe*, **103**, 331-339. https://doi.org/10.1007/s00347-005-1290-7

[41] Arba Mosquera, S., de Ortueta, D. and Verma, S. (2018) The Art of Nomograms. *Eye and Vision*, **5**, Article No. 2. https://doi.org/10.1186/s40662-018-0096-z

[42] Liang, G., Chen, X., Zha, X. and Zhang, F. (2017) A Nomogram to Improve Predictability of Small-Incision Lenticule Extraction Surgery. *Medical Science Monitor*, **23**, 5168-5175. https://doi.org/10.12659/msm.904598

[43] Primavera, L., Canto-Cerdan, M., Alio, J.L. and Alio del Barrio, J.L. (2020) Influence of Age on Small Incision Lenticule Extraction Outcomes. *British Journal of Ophthalmology*, **106**, 341-348. https://doi.org/10.1136/bjophthalmol-2020-316865

[44] Wang, M., Zhang, Y., Wu, W., Young, J.A., Hatch, K.M., II, R.P., *et al*. (2018) Predicting Refractive Outcome of Small Incision Lenticule Extraction for Myopia Using Corneal Properties. *Translational Vision Science & Technology*, **7**, Article No. 11. https://doi.org/10.1167/tvst.7.5.11

[45] Liu, J. and Wang, Y. (2020) Influence of Preoperative Keratometry on Refractive Outcomes for Myopia Correction with Small Incision Lenticule Extraction. *Journal of Refractive Surgery*, **36**, 374-379. https://doi.org/10.3928/1081597x-20200513-01

[46] Hjortdal, J.Ø., Vestergaard, A.H., Ivarsen, A., Ragunathan, S. and Asp, S. (2012) Predictors for the Outcome of Small-Incision Lenticule Extraction for Myopia. *Journal of Refractive Surgery*, **28**, 865-871. https://doi.org/10.3928/1081597x-20121115-01

[47] Allan, B.D., Hassan, H. and Ieong, A. (2015) Multiple Regression Analysis in Nomogram Development for Myopic Wavefront Laser *in Situ* Keratomileusis: Improving Astigmatic Outcomes. *Journal of Cataract and Refractive Surgery*, **41**, 1009-1017. https://doi.org/10.1016/j.jcrs.2014.08.042

[48] Lapid-Gortzak, R., van der Linden, J.W., van der Meulen, I.J.E. and Nieuwendaal, C.P. (2008) Advanced Personalized Nomogram for Myopic Laser Surgery: First 100 Eyes. *Journal of Cataract and Refractive Surgery*, **34**, 1881-1885. https://doi.org/10.1016/j.jcrs.2008.06.041

[49] Liyanage, S.E. and Allan, B.D. (2012) Multiple Regression Analysis in Myopic Wavefront Laser *in Situ* Keratomileusis Nomogram Development. *Journal of Cataract and Refractive Surgery*, **38**, 1232-1239. https://doi.org/10.1016/j.jcrs.2012.02.043

[50] Shapira, Y., Vainer, I., Mimouni, M., Sela, T., Munzer, G. and Kaiserman, I. (2018) Myopia and Myopic Astigmatism Photorefractive Keratectomy: Applying an Advanced Multiple Regression-Derived Nomogram. *Graefe's Archive for Clinical and Experimental Ophthalmology*, **257**, 225-232. https://doi.org/10.1007/s00417-018-4101-y

[51] Caster, A.I., Hoff, J.L. and Ruiz, R. (2004) Nomogram Adjustment of Laser *in Situ* Keratomileusis for Myopia and Myopic Astigmatism with the Alcon LADARVision System. *Journal of Refractive Surgery*, **20**, 364-370. https://doi.org/10.3928/1081-597x-20040701-10

[52] Yu, N., Hou, X., Liu, C., Chen, P., Ye, Y., Lan, M., *et al*. (2025) A Nomogram to Improve the Predictability of High Myopic Astigmatism in Small Incision Lenticule Extraction Surgery. *Journal of Refractive Surgery*, **41**, e65-e72. https://doi.org/10.3928/1081597x-20241126-01

[53] Cao, H., Jhanji, V. and Wang, Y. (2023) Relationship between Postoperative Residual Refractive Error and Preoperative Corneal Stiffness in Small-Incision Lenticule Extraction. *Journal of Cataract and Refractive Surgery*, **49**, 942-948. https://doi.org/10.1097/j.jcrs.0000000000001250

[54] Zhou, J., Gu, W., Gao, Y., He, G. and Zhang, F. (2022) Vector Analysis of High Astigmatism (≥ 2.0 Diopters) Correction after Small-Incision Lenticule Extraction with Stringent Head Positioning and Femtosecond Laser-Assisted Laser *in Situ* Keratomileusis with Compensation of Cyclotorsion. *BMC Ophthalmology*, **22**, Article No. 157. https://doi.org/10.1186/s12886-022-02384-0

[55] Alpins, N.A. and Goggin, M. (2004) Practical Astigmatism Analysis for Refractive Outcomes in Cataract and Refractive Surgery. *Survey of Ophthalmology*, **49**, 109-122. https://doi.org/10.1016/j.survophthal.2003.10.010

[56] Thibos, L.N. and Horner, D. (2001) Power Vector Analysis of the Optical Outcome of Refractive Surgery. *Journal of Cataract and Refractive Surgery*, **27**, 80-85. https://doi.org/10.1016/s0886-3350(00)00797-5

[57] Thibos, L.N., Wheeler, W. and Horner, D. (1997) Power Vectors: An Application of Fourier Analysis to the Description and Statistical Analysis of Refractive Error. *Optometry and Vision Science*, **74**, 367-375. https://doi.org/10.1097/00006324-199706000-00019

[58] Alpins, N. (2021) Comment on: Comparison of Clinical Outcomes between Vector Planning and Manifest Refraction Planning in Small-Incision Lenticule Extraction for Myopic Astigmatism. *Journal of Cataract and Refractive Surgery*, **47**, 141-142. https://doi.org/10.1097/j.jcrs.0000000000000511

[59] Ganesh, S., Brar, S. and Swamy, D.T. (2025) Comparison of Clinical Outcomes and Patient Satisfaction Following SMILE Performed with the VisuMax 800 in One Eye and VisuMax 500 in the Contralateral Eye. *Journal of Refractive Surgery*, **41**, e14-e21. https://doi.org/10.3928/1081597x-20241113-02

[60] Varman, A., Varman, A. and Balakumar, D. (2024) Comparison of Visual and Refractive Outcomes of Keratorefractive Lenticule Extraction for Compound Myopic Astigmatism between Visumax and VISUMAX 800. *Clinical Ophthalmology*, **18**, 3557-3566. https://doi.org/10.2147/opth.s492552

[61] Lee, C., Lian, L., Chen, H., Huang, C., Huang, J., Yang, S., *et al*. (2024) The Outcomes of First-Generation (VisuMax 500) and Second-Generation (VisuMax 800) Keratorefractive Lenticule Extraction Surgeries for Astigmatism. *Scientific Reports*, **14**, Article No. 22224. https://doi.org/10.1038/s41598-024-73303-0