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Hans汉斯

临床常用眼压计研究进展

艾千禧[1]，李　莉[2,3]，葛希龙[1]，周奇志[2,3*]

[1]暨南大学附属第一医院眼科，广东 广州
[2]重庆市江北区爱尔眼科研究所，重庆
[3]重庆眼视光眼科医院屈光手术科，重庆

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摘　要

青光眼是一种由于眼压异常增高导致的疾病，是全球范围内导致视力丧失的主要原因之一。其特征是眼压的病理性增高以及剧烈波动，对视神经和视网膜神经纤维进行压迫，随着病情进展，导致视神经的萎缩以及神经纤维的损伤，最终造成不可逆的视力损失以及视野缺损，居于全球首位不可逆致盲眼病，其发病机制与年龄、遗传、种族等因素有关，但尚未完全明确。青光眼不仅造成患者本身生活质量低下，也给患者家庭造成极大的经济卫生负担。及时有效地诊断和治疗青光眼是至关重要的，为了实现这一目标，眼压的准确测量显得尤为关键。眼压作为评估青光眼风险和跟踪病情变化的重要指标，其测量依赖眼压计。自19世纪以来，约有超过80种以上不同种类眼压计问世，至今有多种眼压计应用于临床，不同的测量设备各有其优势和特点。本文总结了目前临床上常用眼压计的特性，分析其各自的优缺点，并对国内尚未应用于临床的动态眼压监测设备的优点与存在问题进行分析，以期能够使临床医生针对不同情形选择合适的眼压测量设备。

关键词

青光眼，眼压计，眼压

Research Progress on the Clinical Tonometers

Qianxi Ai[1], Li Li[2,3], Xilong Ge[1], Qizhi Zhou[2,3*]

[1]Department of Ophthalmology, The First Affiliated Hospital of Jinan University, Guangzhou Guangdong
[2]Aier Eye Institute of Chongqing, Chongqing
[3]Department of Refractive Surgery, Chongqing Aier Eye Hospital, Chongqing

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*通讯作者。

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Abstract

Glaucoma is a disease caused by abnormally high intraocular pressure (IOP) and is one of the leading causes of vision loss worldwide. Glaucoma is characterized by pathologically elevated intraocular pressure (IOP) and dramatic fluctuations, which compresses the optic nerve and retinal nerve fibers. As the disease progresses, it leads to atrophy of the optic nerve and damage to the nerve fibers, and ultimately causes irreversible loss of vision and visual field defects, and is the world's leading irreversible blinding eye disease, whose pathogenesis is related to age, heredity, and ethnicity, among other factors, and which is yet to be completely clarified. Glaucoma not only causes poor quality of life for the patients themselves, but also creates a great economic and health burden for their families. Timely and effective diagnosis and treatment of glaucoma is crucial, and to achieve this goal, accurate measurement of intraocular pressure (IOP) is especially critical. Measurement of IOP, as an important indicator for assessing glaucoma risk and tracking changes in the condition, relies on tonometers. Since the 19th century, more than 80 different types of tonometers have been introduced, and up to date a wide range of tonometers are used in clinical practice, with each of the different measuring devices having its own advantages and characteristics. This article summarizes the characteristics of the commonly used tonometers in clinical practice, analyzes their respective advantages and disadvantages, and analyzes the advantages and problems of the dynamic intraocular pressure (IOP) monitoring devices that have not yet been applied to clinical practice in China, with the aim of enabling clinicians to choose the appropriate IOP measurement devices for different situations.

Keywords

Glaucoma, Tonometers, Intraocular Pressure

1. 引言

青光眼是目前全球第二大致盲性眼病，至 2040 年全球青光眼患者人数将增加到 1.118 亿[1]。青光眼是由于眼压的病理性增高以及剧烈的波动，对视神经和视网膜神经纤维进行压迫，导致视神经的萎缩以及神经纤维的损伤，最终造成不可逆的视力损失以及视野缺损，其发病机制尚未完全明确。眼压的高低对青光眼的早期筛查、诊断和治疗方案的制定及治疗效果的判定具有十分重要的作用。眼压的测量主要依赖眼压计，自 19 世纪以来，至今约有 80 种以上的眼压计问世，根据是否接触人眼，主要分为接触式与非接触式，不同的眼压计根据其特性适用不同临床场景。本文通过对临床常用眼压计的特性与优缺点作一综述，以期帮助临床医生针对不同临床情景选择合适的眼压测量装置，尽可能得到相对真实的眼压。

2. 压平式眼压计

1955 年 Goldmann 发明了具有代表性的眼压测量装置——Goldmann 压平式眼压计(Goldmann Applanation Tonometer, GAT)，一直以来该眼压计被视为测量眼压的金标准[2]，即最准确和最推荐的标准，所有其他眼压计都要与之比较。GAT 是基于 Imbert-Fick 原理设计的，其测量头直径为 3.06 mm，将测量头

压平 7.35 mm² 的角膜面积，所需要的压力即为眼内压[3]。虽然 GAT 多来以内一直被奉为眼压测量的金标准，但是其测量值未必是最精确的，首先其测量值低于真实的眼内压[4]，其次受角膜曲率、角膜硬度、角膜厚度等因素的影响，其中最重要的便是中央角膜厚度(CCT)。GAT 是基于 CCT 为 520 μm 设计的，当 CCT 大于 520 μm 时，测得眼压会比实际值高，而当 CCT 小于 520 μm 时，眼压会比实际值降低[5]。GAT 需连接到裂隙灯上，用荧光素钠染色，医生用眼睛来判断两个荧光环是否相切，依赖医生的经验，所以主观性较强[6]，测量结果还与荧光素钠的使用量有关[7]。并且 GAT 测量时只能采用坐姿，直接接触到人的角膜，需要使用到表面麻醉及荧光素钠染色，操作繁杂，需要被测者高度配合，存在角膜损伤、感染、麻醉药物毒性及过敏反应等风险，因此在临床工作中的使用受到限制。对于无法采取坐位的患者，便携式压平式眼压测量装置 Perkins 眼压计应运而生，该眼压计克服了 GAT 测量时必须采用坐位的缺陷，但是和 GAT 一样，Perkins 眼压计也受角膜组织特性等影响，存在 GAT 的诸多不足[8]。

3. 非接触式眼压计

非接触式眼压计(Non-contact tonometry, NCT)最初是由蔡司公司设计，并由 Grolman 进一步研发[9]。NCT 同样是基于 Imbert-Fick 原理设计，利用高速气流将角膜一定面积(约直径 3.60 mm)压平，激光发射器发出激光，激光信号经光电系统转换为眼压。NCT 学习曲线短、无需麻醉、不接触被测者的角膜、测量快捷，因而更容易被患者所接受，临床上将其作为眼压的首选测量方式。NCT 同 GAT，都是基于 Imbert-Fick 原理，因此也同受角膜参数的影响，其中 CCT 对 NCT 测量结果影响最为显著，随着 CCT 的升高，NCT 的测量值也会偏高[10] [11]，并且比起 GAT，CCT 对 NCT 测量结果影响更强[12]。目前国际上关于 NCT 对比金标准 GAT 测量结果偏高还是偏低争论不一[13] [14]，既往研究指出当 CCT > 539 μm 时，NCT 相较 GAT 的准确性下降[15]，眼压 ≥ 40 mmHg 或≤8 mmHg 时，NCT 测量结果相较 GAT，误差会显著增大[16]，在角膜水肿[17]等病理状态下，这种差异还会增大，并且不同型号、不同品牌的 NCT 所测得眼压也不尽相同[18]。虽然 NCT 测量简便，非常快捷，能常规用于青光眼的筛查，但是 NCT 的测量结果绝不能替代 GAT，特别是对于高眼压症、青光眼患者以及有青光眼危险因素的人群。

4. 回弹式眼压计

回弹式眼压计(iCare rebound tonometer)于 1996 年被发明[19]，其发明者 Kontiola 运用电磁感应原理，将探头接触角膜并减速，连续测量 6 次后将减速度转换成眼压读数。回弹式眼压计作为一款接触式眼压计，相比 GAT，学习曲线短，容易携带，测量不受体位影响，也无需表面麻醉和角膜染色，测量轻柔，被测者基本感觉不到疼痛，特别适用于无法耐受 NCT 喷气的儿童[20]。虽然会增加测量成本，iCare 每次进行测量都会更换无菌探头，降低了交叉感染风险。iCare 已被证实具有良好的重复性[21]，在正常眼压范围，与金标准 GAT 相比具有良好的一致性[22] [23]，但是在高眼压的情况下，iCare 的测量值可能会显著低于 GAT [24]。iCare 也可以用于角膜水肿[25]与其他病理角膜状态下患者的测量[26]。对于角膜术后诸如角膜移植的患者，患者疼痛感明显，敏感度高，无法耐受 NCT 的喷气，且要预防感染，这种情况下 iCare 同样适用[27]。iCare 同 GAT 一样，同样受角膜因素的影响，如角膜厚度、角膜曲率等[28]。Yamashita 等人[29]发现 iCare 在角膜不同位置测得眼压不同，其中角膜中央测得值相比鼻侧和颞侧更加接近 GAT，如今 iCare 在新款设备如 iCare-ic100 上加入了探头识别功能[30]，当探头位置正确时显示为绿灯，位置不正确时显示为红灯，这样能在一定程度上减少测量时的误差。另外，iCare 的家用式眼压计(iCare Home)可以让患者在家中自行进行眼压测量，对眼压进行动态监测，为青光眼患者的眼压管理和治疗提供依据和参考[31]。

5. 动态轮廓眼压计

2005 年，Kanngiesser [32]利用帕斯卡原理，即当对封闭流体施加压力变化时，压力变化不会减弱地传递到流体的所有部分及其容器的壁上，发明了动态轮廓眼压计(Dynamic contour tonometer, DCT)。由于设计原理不同，这种眼压计不同于其他接触式眼压计如 GAT，DCT 前置一个凹面探头，内置微型压力传感器，探头弧度与角膜相似，当探头与角膜相匹配时很少引起或者不引起角膜发生形变，避免了切线力和角膜发生形变影响测量，因此理论上不受角膜厚度、角膜曲率等角膜因素的影响[33] [34]，且 DCT 受角膜因素影响较小，有助于屈光术后患者眼压的测量[35]。研究证明 DCT 与金标准 GAT 有良好的相关[36]，但是 DCT 测得眼压值往往高于 GAT [37]，因此不能简单地代替 GAT 的测量值[38]。DCT 除了测量眼压外，同时还能提供眼脉动振幅(OPA)，并籍由 OPA 的高低来推断与青光眼的关系[39]。然而 DCT 测量需要连接在裂隙灯上，要求专业的医生来进行测量，具有一定的测量门槛，且被检需要使用表麻药，保持测量姿势至少 8 秒，配合要求高，在测量眼球震颤、儿童等配合度较差患者时，DCT 可能就不太适用。

6. 可视化角膜生物力学分析仪

可视化角膜生物力学分析仪(Corneal visualization Scheimpflug technology, Corvis ST)发行于 2011 年[40]，是一种较新的非接触式眼压计，虽然同样基于 Imbert-Fick 原理设计，但是该非接触式眼压计搭载 Scheimpflug 高速摄像机，当喷气气流将角膜由凸面压至扁平时测量眼压，Scheimpflug 摄像机捕捉 8.5 毫米直径的中央角膜，并以高分辨率和超过每秒 4000 帧的速度记录气流喷射引起的角膜变形及其恢复正常形状的过程，通过内置电脑分析，获得 Corvis-IOP、CCT、角膜生物力学参数等指标。既往研究表明 Corvis-ST 低于 GAT 测得眼压值，但是二者的结果具有良好相关性[41] [42]。Corvis-ST 通过纳入年龄、角膜厚度、角膜形态等因素，得出了将 Corvis-IOP 进行修正的 bIOP [43]，已有研究证实 bIOP 具有良好的准确性和可重复性[44]，并且与体内实际眼压相当，不受 CCT 和生物力学因素等影响[45]，在测量屈光术后病人的眼压中也会更加准确[46]。Corvis-ST 测量过程不接触角膜，无需滴用表麻药，测量便捷，不仅可以测得眼压和角膜生物力学参数，还能用于圆锥角膜的诊断[47]，深受临床医生的青睐。

7. 眼部反应分析仪

眼部反应分析仪(Ocular Response Analyzer, ORA)问世于 2005 年，是一种利用快速空气脉冲和光电系统测量眼压的非接触式眼压计。在平视状态下，ORA 通过气流使角膜向内移位，角膜变凹，而后气流停止，角膜向外移位，最后恢复正常，得到角膜双向压平过程，这样就得到了两次眼压测量值，由于脉冲气流的动态性以及角膜生物力学的影响，两次测量结果并不相同。将两次测量结果取平均值，得到模拟 Goldmann 眼压计的眼压值(IOPg)，并根据计算机软件提供了去除角膜生物力学特性对眼压的影响后得出的校正值，即角膜补偿眼压(IOPcc)。与 GAT 相比，ORA 的眼压测量结果显著偏高，特别是在高眼压的情况下[48]。已有研究证明，IOPcc 不受角膜厚度的影响[49] [50]，因此相较 GAT，IOPcc 可能更好地反应屈光术后的真实眼压[51]。ORA 是目前唯一能够提供角膜滞后(CH)和角膜阻力因子(CRF)的设备，利用光电系统记录角膜对快速空气脉冲的反应，得到角膜的内向与外向位移之差角膜滞后(CH)，即角膜组织吸收和分散能量的能力，反应了角膜的粘弹性，并可由 CH 推算出角膜阻力因子(CRF)，CRF 表示角膜的整体阻力，反应了角膜的整体硬度，二者共同代表了角膜的生物力学特性。CH 和 CRF 在临床工作中有诸多用途，例如角膜屈光术后，CRF 和 CH 共同降低，表示角膜生物力学稳定性降低[52]，低 CH 也被证实与青光眼相关[53]，并且 CH 还可以帮助诊断角膜病变的患者例如圆锥角膜[54]。ORA 有着非接触式眼压计的诸多优点，比如无接触式测量，无需表面麻醉，快速等优点，但对于不能配合、无法固视的患者不能准确的测量眼压。

8. 动态眼压检测装置

眼压具有昼夜节律性及波动性，正常人 24 小时眼压波动小于 8 mmHg，青光眼患者的 24 小时眼压波动性大于 8 mmHg [55]，而青光眼患者眼压峰值大多出现在夜间[56]，眼压峰值及波动性在夜间使用上述眼压计难以测得，所以采用 24 小时动态监测眼压对于管理特别是高眼压和慢性青光眼患者十分必要。动态眼压的监测设备目前已经实现，主要分为植入式及佩戴式。植入式通常需要与白内障手术同时进行，并且有严格的适用和排除标准，而佩戴式是一种非侵入式的测量设备，通过佩戴装载微型传感器类似角膜接触镜的特殊设备，实现眼压的无创性持续测量。早在 2001 年，Rizq 等[57]发明了夹带式压力传感器，能够在脉络膜表面测量眼压，为后续的可植入式眼压监测设备提供了参考。如今，具有代表性的植入式眼压检测设备是由德国 Implandata Ophthalmic Products GmbH 出品的 Eyemate，其通过内置传感器感受眼压的变化，Eyemate 已经被证实在人体中是安全的，并且其测量结果准确可信，与 GAT 具有良好的相关性[58]。相比植入式测量设备，由瑞士 Sensimed 出品的角膜接触式 Triggerfish (Triggerfish CLS)因其无创、便于佩戴和拆卸的特点可能更受临床青睐，该设备基于监测角膜曲率的微小变化来测量眼压。Triggerfish CLS 具有良好的患者耐受性及安全性[59]，然而 CLS 的测量值与 GAT 测量值存在显著差异[60]，CLS 测量值可能只能代表此刻的相对眼压，并不能代表此时的准确眼压值。虽然 CLS 的准确性需要进一步讨论，但是其优点在于眼压的监测，CLS 测量结果显示青光眼患者的夜间峰值出现早且高于正常人[61]，且 CLS 有助于正常眼压性青光眼患者的诊断及治疗[62]。然而动态眼压监测设备尚且有许多不足，诸如超过一定距离接收器就无法接受眼压数据，植入性设备面临感染风险以及失效后难以取出的问题，角膜接触式传感器因眼内蛋白质等附着造成信号漂移[63]，佩戴者出现结膜充血、视物模糊等不良反应[64]，未来还有许多问题等待去解决。

9. 结语

回顾眼压计的发展历程，从金标准 Goldmann 眼压计到可以排除角膜生物力学影响的 Corvis-ST，再到如今可以进行动态监测眼压的测量装置，我们可以看到眼压计的准确度和可适用性与日俱增，但是无论哪一种眼压测量设备都并非完美。对于常规的眼压测量设备来说，诸如 NCT、Corvis-ST 等，其舒适性和准确性已经有目共睹，并且有些设备已经加入角膜测厚功能、校正眼压公式来自动校正眼压，使测量结果更加准确，未来或将针对特定患者(如固视不良者、无法坐位者)的测量方法进行改良。对于动态眼压监测设备来说，首先考虑的是非接触式及无创的设备，但是角膜接触式的动态眼压监测设备由于受角膜的组织结构特性等影响，目前准确度和稳定性尚不理想。植入式眼压测量设备由于严格的使用标准以及较高的风险也使其在临床中应用受限。如何将动态眼压监测设备的准确性和安全性进一步提升是未来急需解决的问题，但是可以预见的是，随着技术和工艺的发展，无论是植入式还是佩戴式，精确性和灵敏度会越来越高，对于监测青光眼患者的眼压变化，治疗以及延缓病情进展有着莫大的帮助。

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