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反肩关节置换术的演进与突破

——基于巨大肩袖撕裂治疗的系统性综述

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摘 要

巨大肩袖撕裂(massive rotator cuff tear, MRCT)及其继发的肩袖撕裂关节病(Cuff Tear Arthropathy, CTA)常导致肩关节功能丧失。反肩关节置换术(Reverse Total Shoulder Arthroplasty, RTSA)通过“倒置球臼”设计重塑肩关节生物力学，利用三角肌代偿肩袖功能，现已成为不可修复性MRCT和老年复杂肩关节疾病的核心治疗手段。本文基于巨大肩袖撕裂的肩关节置换治疗，阐明RTSA从功能代偿到生物力学适配的转型逻辑，综述RTSA假体的演进、适应症、临床疗效及并发症，为临床实践提供理论依据，并展望智能精准化发展方向。

关键词

巨大肩袖撕裂，反肩关节置换术，假体设计，生物力学

Evolution and Breakthroughs of Reverse Total Shoulder Arthroplasty

—A Systematic Review Based on the Treatment of Massive Rotator Cuff Tears

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Abstract

Massive rotator cuff tear (MRCT) and its secondary cuff tear arthropathy (CTA) often lead to severe dysfunction of the shoulder joint. Reverse total shoulder arthroplasty (RTSA), with its "reversing the position of the convex and concave surface" design, reconstructs shoulder biomechanics by utilizing the deltoid muscle to compensate for rotator cuff deficiency, and has become the cornerstone treatment for irreparable MRCT and complex shoulder pathologies in elderly patients. This review focuses on shoulder arthroplasty for MRCT, elucidating the transformative rationale of RTSA from functional compensation to biomechanical adaptation. It comprehensively summarizes the evolution of RTSA prostheses, expanded indications, clinical efficacy, and complications, providing theoretical support for clinical practice. Future perspectives on intelligent and precision-oriented development directions are also discussed.

Keywords

Massive Rotator Cuff Tear, Reverse Total Shoulder Arthroplasty, Prosthetic Design, Biomechanics

1. 引言

巨大肩袖撕裂(massive rotator cuff tear, MRCT)是肩关节疾病中极具挑战性的临床问题，常伴随肌腱回缩、脂肪浸润及肌肉萎缩，导致肩关节生物力学失衡和严重功能障碍。传统非手术治疗对活动需求低的老年患者效果有限，而早期手术方案如部分修复、补片增强或肌腱转位虽能缓解症状，但再撕裂率高、技术要求严苛且长期疗效不稳定，尤其在肩袖功能严重丧失的情况下难以实现肩关节功能重建。如何有效恢复 MRCT 患者的肩关节稳定性和活动功能，成为了骨科领域亟待解决的难题。

肩关节置换术的发展为 MRCT 的治疗提供了新思路。早期的半肩关节置换术(HA)和解剖型全肩关节置换术(ATSA)虽在骨关节炎和骨折治疗中取得一定成效，但其依赖完整肩袖功能的设计在 MRCT 患者中暴露出假体松动、盂窝磨损和术后不稳定的缺陷。直至 20 世纪 80 年代，Grammont 提出反肩关节置换术(Reverse Total Shoulder Arthroplasty, RTSA)，通过"倒置球臼"的设计将旋转中心向内向下移动，利用三角肌代偿肩袖功能，彻底改变了 MRCT 的治疗格局。

本文旨在系统综述 RTSA 的假体设计从功能代偿到生物力学适配的演进，适应症从肩袖关节病、肩关节骨折到巨大肩袖撕裂、翻修手术的扩展，临床疗效的优势及并发症的防治，以及未来结合 3D 打印、人工智能的发展方向，为临床决策提供理论依据，并推动 RTSA 技术的进一步优化与创新。

2. 巨大肩袖撕裂概念及临床治疗

巨大肩袖撕裂(massive rotator cuff tear, MRCT)通常定义为累及至少两条肌腱(如冈上肌和冈下肌)，或单一肌腱撕裂长度超过 5 cm，或 MRI 冠状面和矢状面收缩撕裂大于 2 × 2 cm 的全层肩袖撕裂[1] [2]。Schumaier 等专家组对巨大肩袖撕裂形成了共识，定义为或在轴向或冠状面中回缩至关节盂边缘的撕裂，或在矢状面中暴露至少三分之二的大结节的肩袖撕裂[3]。巨大肩袖撕裂常伴随显著的肌腱回缩、脂肪浸润(Goutallier 分级 ≥3)及肌肉萎缩，导致肩关节生物力学失衡，临床上主要表现为剧烈疼痛、主动外展和

外旋功能减退或丧失，有的患者甚至会出现假性瘫痪(pseudoparalysis) [4]。MRCT 可进一步分为可修复与不可修复两类，后者常因肌腱质量差或肌肉不可逆退变而导致术中无法直接缝合修复。此外，长期未治疗的 MRCT 还可能进展为肩袖撕裂关节病(rotator cuff arthropathy)，表现为肱骨头上移、关节盂“髋臼化”及骨关节炎[5]，进一步加剧患者疼痛及功能障碍。如何有效恢复 MRCT 患者的肩关节功能是骨科大夫面临的巨大挑战。

目前 MRCT 的治疗分为非手术与手术两类。物理治疗、类固醇注射及抗炎药物治疗等非手术方案通常适用于活动需求低或合并严重基础疾病的老年患者，非手术治疗的长期疗效有限，失败率高达 30%，最终仍需要转为手术处理[6]。手术包括伴或不伴移植物增强部分肩袖修复、补片增强(如真皮异体移植物或阔筋膜移植)、上关节囊重建(superior capsule reconstruction, SCR)、肩峰下球囊扩张技术、肌腱转位(如背阔肌或下斜方肌转位)和反肩关节置换术(Reverse Total Shoulder Arthroplasty, RTSA)。关节镜下部分修复肩袖时联合肱二头长头腱转位可显著改善术后的疼痛和活动功能康复，但再撕裂率仍达 36% [7]。SCR 则恢复了肩关节上方的稳定性，短期疗效显著，但长期临床效果仍待验证，且对术者技术要求较高。肌腱转位在年轻患者的治疗中展现出了一定的潜力，但术后血肿和转位肌腱断裂等并发症出现率约 18% [8]。RTSA 能够显著缓解肩关节疼痛，恢复日常活动功能，已成为治疗老年患者 MRCT 的金标准。

3. 肩关节置换术的发展历史

肩关节置换技术的早期探索以半肩关节置换术(HA)和解剖型全肩关节置换术(ATSA)为主，主要应用于肩关节炎、骨折及骨肿瘤的治疗。HA 保留了盂窝结构，但长期随访显示其存在盂窝磨损率高、疼痛缓解不彻底等问题。ATSA 符合肱骨头和盂窝的解剖结构，但其成功率高度依赖完整的肩袖功能，对于合并严重肩袖损伤或骨缺损的患者，常因假体不稳定、盂窝松动或肩袖失效而影响预后[9]。二者在巨大肩袖撕裂的治疗中效果都不甚令人满意。

为解决上述问题，20 世纪 80 年代后，学者开始探索设计非解剖型假体，反肩关节置换术(RTSA)登上了历史舞台，它有着颠覆以往解剖置换术的“倒置球臼”的设计，将肱骨侧改为凹面、肩胛盂侧改为球面，有效地利用三角肌代偿了肩袖功能。早期 Neer 提出的限制性假体试图通过增加盂窝深度限制脱位，但过度的约束导致假体受到的应力过于集中，反而加速了假体的松动[9]。Grammont 于 1985 年改进提出了半限制性的假体设计，利用骨水泥固定假体，显著改善了置换术后假体的稳定性[10]，也成为了如今不断发展完善的反肩置换假体的基石。

4. 反肩关节置换假体设计与生物力学演进

RTSA 的假体设计自 Grammont 提出首款半限制型假体以来经历了显著演变。初始 RSA 假体设计的核心是通过将旋转中心移动到更内侧和更下方的位置，将肱骨移向远端，增加了三角肌的外展力臂，以补偿肩袖功能的缺失。尽管它最初设计用于肩袖关节病，但现在的适应症包括粉碎性肩关节骨折、类风湿性关节炎和严重骨关节炎[11]。

因为早期 RTSA 假体存在肩胛骨切迹、肩峰骨折及活动范围受限等缺陷，促使后续技术进一步优化。近年来，为应对这些问题，现代假体设计逐步引入了侧移(lateralization)的概念，包括关节盂侧移(glenoid lateralization)和肱骨侧移(humeral lateralization)，通过增加盂球偏心距或肱骨外侧偏移来改善三角肌张力，增加关节的稳定性[12] [13]。

其中，关节盂侧移(4~10 mm)通过盂球旋转中心(center of rotation, COR)的外移或下移来扩大肩关节活动范围，并减少肩胛骨切迹的发生。Liu 等人[14]的体外生物力学研究表明，关节盂侧移可减少内收时的肱骨－肩胛颈撞击，增加三角肌张力，增大免撞击内收外展角度，改善患者的外旋功能(+15°)，但

超过侧移 8 mm 时会使肩胛骨切迹发生率从 12%升至 21%。Boileau 等人[15]提出了骨性侧移技术(Bony Increased-Offset RSA, BIO-RSA)，通过在基座下方植入自体骨实现侧移，显著降低了肩胛骨切迹发生率(18%)，同时改善了外旋功能，然而 BIO-RSA 依赖移植骨的愈合，存在骨吸收和早期基座松动的风险[16]。金属侧移技术(Metallic Increased-Offset RSA, MIO-RSA)通过几何优化关节盂基座或肱骨组件实现侧移，避免了 BIO-RSA 移植骨的并发症[17]，生物力学分析表明，金属侧移技术通过分散应力，可将螺钉–骨界面峰值应力从 18.3 MPa 降至 12.1 MPa，从而减少假体松动的风险，更适合骨质疏松患者[18]，但过度侧移可能增加肩胛骨应力性骨折的风险。135°或 145°颈干角的肱骨侧移假体则进一步优化了关节外旋能力和假体稳定性，通过降低肱骨–肩峰撞击风险使内旋角度提升至 22°，但可能增加肱骨柄尖端应力骨折风险(由传统设计的 0.9%升至 3.4%) [19]。Elwell 等人通过计算机模拟得出，较传统 Grammont 假体，结合关节盂旋转中心侧移(4 mm)和肱骨侧移(145° NSA)的假体设计可将术后活动范围提升 31%~39%，假体松动风险降低至 1.2%，但仍需术者平衡过度侧移导致的肩胛骨应力骨折的风险[20]。

早期假体的另一缺陷是关节盂基座固定不稳，尤其在患者骨量不足或伴有畸形时更为显著。传统的关节盂基座依赖中央长螺钉和四枚外周螺钉固定，但在患者伴有严重骨缺损时易发生微动。多种研究显示，使用更多螺钉(如将外周螺钉增加到 6 枚)，增加中心和外周孔螺钉的长度，使用定制基座等，都可以有效增加基座的稳定性[21]-[23]。为此，增强型基座(如楔形基座或偏心基座设计)和三维术前规划技术被引入，以优化螺钉轨迹和骨接触面积[24]。基座固定技术的发展进一步增强了反肩关节置换术后假体的稳定性。Krupp 等人的临床研究对比了标准基座与迷你侧移基座(含肱骨侧移假体和增强型基座)，发现后者显著提升了患者术后肩关节的前屈和外旋能力，且肩胛骨切迹发生率更低[25]。

由于 RSA 不仅在初次手术中，而且在翻修手术中的使用率越来越高，因此保留近端骨量的无柄反向肩关节置换(Stemless RSA)应运而生，最大限度地减少了肱骨柄相关并发症，如术中骨折、干骺端应力遮挡和创伤性假体周围骨折等。此外，在翻修手术中，它可以减少肱骨柄取出困难、去除过程中假体周围骨折等问题[26]。生物力学研究表明，无柄假体在反向肩关节置换中会承受更大的剪切力和扭矩，这导致其稳定性高度依赖干骺端骨密度[27]。此外，有限元分析显示，无柄假体的应力分布更接近正常肱骨近端，能有效降低应力遮挡风险[28] [29]。技术层面，无柄假体对肱骨头截骨高度和角度的精确性要求更高，合理应用软件进行术前三维规划及术中透视有助于优化假体位置[30] [31]。

此外，模块化假体的出现允许术中灵活调整肱骨与关节盂组件，更加个体化的同时也减少翻修难度，但其金属衬垫可能引发聚乙烯磨损或松动[32]。总而言之，反肩关节置换假体的演变反映了手术从单纯满足患者功能代偿向生物力学适配及最大程度减少并发症的转变。

5. 反肩关节置换适应症

反肩关节置换术(RTSA)的适应症近年来不断扩展，已从最初的肩袖关节病(CTA)延伸至多种复杂肩关节病变，包括肩袖功能严重缺失的巨大肩袖撕裂，以及此类患者因肩袖动态稳定性丧失而导致的假性瘫痪[33]。其次，RTSA 已成为老年患者肱骨近端三或四部分骨折的首选治疗方案，相比半肩置换，其术后功能恢复更好且并发症更少，尤其在骨质疏松的患者中优势更为显著[9] [34]。此外，RTSA 在翻修手术中表现突出，适用于解剖型肩关节置换失败(如肩袖失效、假体松动等)或初次半肩置换术后肱骨头移位的情况，尽管翻修手术并发症率较高，但功能改善显著[35] [36]。近年来，RTSA 还被用于肩关节肿瘤切除后的功能重建，尤其是肱骨近端骨肿瘤需广泛切除时，通过定制 RTSA 假体可恢复肩关节基础功能，但需权衡患者预期寿命与手术风险[37] [38]。目前年轻患者(<65 岁)的适应症正在逐渐放宽，研究显示其早期临床结果与老年患者相当，但需关注远期假体存活率[39] [40]。

6. 反肩关节置换治疗巨大肩袖撕裂的临床疗效与长期随访

与 ATSA 相比，RTSA 在术后前屈和外展功能恢复上更具优势，并显著降低了术后不稳定性风险。对于合并肩袖撕裂关节病(Cuff Tear Arthropathy, CTA)的患者，RTSA 可将前屈活动度从术前的 52˚提升至 126˚，显著改善患者日常生活能力[41]。在老年人群中，RTSA 的疗效尤为突出，Patel 等人的中期随访研究显示，75 岁以上患者术后前屈角度从 82˚提升至 133˚，疼痛评分(VAS)从 6 降至 2，且 5 年假体生存率达 98% [42]。相比之下，ATSA 在肩袖功能不全患者中易发生术后肩袖继发性撕裂(3.7%)，需翻修手术的风险更高[43]。

长期随访研究证实，RTSA 在假体生存率和关节功能维持方面表现比较稳定[42]，在复杂解剖条件下的长期稳定性也得到了多项研究的验证，在现代假体的加持下，术后假体松动率、10 年翻修率都大大降低[44]。长期并发症方面，肩胛骨切迹发生率随假体侧移设计优化从传统设计的 17.7%降低至 11.3%，且严重切迹比例从 18%降至 8% [45]。在老年患者中，RTSA 的长期功能维持同样可靠。Gross 等人对 75 岁以上患者的 5 年随访表明，RTSA 组术后前屈角度(126˚)和满意度(94%)与 ATSA 组(155˚, 91%)接近，且翻修率仅为 1.9% [41]。

综上，RTSA 通过优化三角肌生物力学，代偿肩袖功能，在活动度恢复、疼痛缓解及并发症控制方面表现优于传统 ATSA，且长期疗效和假体生存率在技术进步推动下持续优化，尤其在复杂解剖形态和老年人群中的表现尤为突出。

7. 反肩关节置换术后并发症及其防治策略

假体松动是 RTSA 术后早期常见并发症，发生率约为 4.3%，其发生机制主要与假体–骨界面剪切应力异常集中相关，多因软组织张力缺乏、关节盂骨量不足导致基座螺钉固定不牢、假体位置不良(如基座倾斜角 > 10˚)引发杠杆效应、术后早期过度外旋导致微动界面纤维组织长入失败导致，危险因素包括肩关节既往手术史、肥胖及术中过度松解三角肌等[46] [47]。可进行以下防治策略：术前通过三维 CT 重建评估骨缺损，采用骨移植(如自体肱骨头结构性植骨)或增强型基座(如楔形基座)优化初始稳定性；术中使用导航系统控制基座倾斜角在±5˚以内，并采用 6 枚锁定螺钉(中央 + 外周)分散应力，精准调整假体偏心距、避免软组织过度松解，确保关节盂骨与假体接触面准备充分；术后早期阶段限制外旋活动等。

肩峰及肩胛骨应力性骨折发生率约 5.3%，与术中肩峰过度牵拉或术后过度负重相关[47]，因此高风险患者(如严重骨质疏松者)术中需避免肩峰过度剥离，并在术后及时使用辅助器具减少肩部负荷。

感染风险与既往多次手术史显著相关，其病理机制涉及假体表面生物膜形成和宿主免疫抑制状态。术后感染率约为 1.2%~1.6%，既往肩关节手术史(尤其是开放性手术)、肥胖等因素会显著增加感染风险[48]。预防措施需多阶段干预：术前优化患者的免疫状态，筛查并纠正贫血(Hb < 10 g/dL 时感染风险增加 2.1 倍)、控制糖尿病(HbA1c > 7.5%时感染率升至 4.3%)；术中严格无菌操作，采用万古霉素骨水泥(降低感染率 37%)和脉冲冲洗；术后密切监测炎症指标，6 周口服头孢呋辛预防迟发性感染[48]。对于高危患者，建议使用含银离子涂层的基座组件，其体外抑菌效果可达 99.8% [49]。

神经损伤中腋神经麻痹发生率约 1.8%，主要发生在关节盂暴露时过度牵拉三角肌后束所致，可能导致术后肩部无力。术中在处理关节盂下方时应注意避免过度牵拉或电刀损伤[46]，可通过“安全三角”技术(肩胛下肌下缘至腋神经平均距离 3.2 cm)定位神经走行，并使用神经监测设备实时预警。对于合并臂丛神经病变者，术前肌电图检查可显著降低术中神经损伤风险。

为减少手术并发症的发生，术前在患者选择上应多加考量，避免在严重骨质疏松或既往多次肩关节手术的患者中盲目选择 RTSA。通过 CT 三维重建精确测量关节盂倾斜角及骨缺损，定制个性化假体，纠正关节盂倾斜度，联合骨移植或增强基座来提高假体稳定性，保留三角肌止点，避免软组织过度松解等，

都是减少并发症的有效手段。双侧手术患者两次手术间隔应 ≥3 个月，以降低血栓及假体松动风险[49]。同时，术后早期阶段应限制肩关节外旋及负重，逐步过渡至主动活动，并注意让患者长期定时复查。

8. 未来研究方向

模块化和可转换性假体使手术更具有个体化调整，还需探索更灵活的模块化设计，并结合生物力学数据优化各组件之间的匹配性。Ajibade 等人[50]经过 5~10 年随访提出，无柄假体术后拥有更低的松动率(0.2%)和并发症率(11.2%)，未来可结合 3D 打印技术开发个性化无柄假体，进一步优化骨接触面的固定效果。假体侧移设计增加了关节稳定性，但过度侧移可能增加肩胛骨应力性骨折的风险，未来需通过有限元分析结合临床数据，明确不同解剖形态下的最佳侧移参数，并开发动态调节假体。术后感染和假体松动仍是假体失效的主要原因，Markes 等人研究提出可采用抗菌涂层或骨诱导材料来提升假体生物相容性，此外，可降解镁合金假体的探索可能为年轻患者提供短期力学支撑与促进长期骨愈合的双重优势[51]。

微创前外侧入路和肿下肌保留可减少术后僵硬和神经损伤，未来需开发专用微创工具，并建立标准化软组织平衡评估体系。计算机导航和机器人辅助能显著提升假体定位的精度，未来需整合人工智能(AI)实时分析解剖形态，并开发低成本便携式导航设备。增强现实(Augmented reality, AR)与混合现实(Mixed Reality, MR)技术具有真实的可视化数据，结合患者个体化 3D 模型，可模拟不同假体植入效果并优化术前计划[52] [53]，进而提高手术准确性。

9. 总结与展望

反肩关节置换术(RTSA)通过颠覆性的“倒置球臼”设计，彻底改变了巨大肩袖撕裂(MRCT)的治疗范式。随着假体设计的生物力学优化，RTSA 在降低手术并发症、提高术后功能恢复方面不断取得突破。适应症也从传统的老年 CTA、MRCT 扩展至复杂肱骨近端骨折、翻修手术及肿瘤重建领域。然而，术后并发症如感染、应力性骨折及神经损伤仍需通过精准术前规划、软组织平衡及个体化假体选择加以防控。

未来研究需聚焦于模块化假体与 3D 打印技术的结合，以实现更精准地解剖适配；动态侧移参数的生物力学优化可降低肩胛骨应力性骨折风险；抗菌涂层与可降解材料有望提升假体生物相容性，降低感染率。计算机导航、人工智能及增强现实技术将推动手术精准化与微创化发展。多学科协作(如生物工程、材料科学与数字医学)将是推动 RTSA 技术革新的关键。通过整合临床需求与前沿科技，RTSA 有望从“功能代偿”迈向“生物功能重建”，最终实现肩关节疾病的精准化、智能化治疗。

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