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Narrative Review

Are cartilage repair and restoration procedures in the knee without respecting alignment fruitless? A comprehensive review

Robin Martin[a,*] and Roland P. Jakob[b,c]

[a] Department of Orthopedic Surgery and Traumatology, Lausanne University Hospital, Lausanne, Switzerland
[b] Orthopedics Cantonsspital, Fribourg, Switzerland
[c] University of Bern, Bern, Switzerland

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ABSTRACT

Introduction: Both in the tibio-femoral and the patello-femoral (PF) joint, malalignment results in chronic overloading and plays a central role in the initiation, location and progression of cartilage defects. A vicious cycle is present, where erosion and secondary ligament attenuation promote further overload with progressive transition to osteoarthritis.
Objectives: To synthetize what is currently known about the importance of realignment osteotomies (OT) for cartilage repair in the knee.
Methods: We conducted a comprehensive literature search in PubMed and Medline databases. Original articles, systematic reviews, and meta-analysis were considered. References of selected articles were also analyzed manually. Data from selected publications were summarized in a narrative review.
Results: Despite the proven benefits of OT of redistributing mechanical load and establishing a favorable biomechanical environment, staged or concomitant OT is not standardized in cartilage repair today. Many cartilage surgeries could be improved if they allowed axial realignment in the preliminary necessity of patient care. Therefore, every patient designated for cartilage repair should have preoperative diagnostic investigations for malalignment. For lesions affecting the tibio-femoral joint, the break point for OT was lowered in the last decade from 5° to 3° of mechanical axis malalignment. In the PF joint, contact pressure is higher, with malalignment often related to several biomechanical factors. With current failure rates of cartilage repair being more prevalent in the PF joint, an approach where all contributing factors are addressed should be implemented.
Conclusion: Osteotomy remains the cornerstone improving the long-term durability of cartilage restoration in overloaded compartments.

Introduction

The first surgical osteotomy of the knee was performed in 1826 by John Rhea Barton for an ankylosed knee and the first book devoted to osteotomy was already published by Macewen in 1880.[1,2] Osteotomies gained progressive acceptance throughout Europe but were utilized mostly for corrections of deformities. Until the mid-twentieth century, surgical approaches for the treatment of osteoarthritis of the knee were limited, with arthrodesis as the main option for the most severe cases. Application of osteotomy for the treatment of unicompartmental osteoarthritis was first reported in Europe by Brittain in 1948 and then by Jackson in 1958.

* Corresponding author: Robin Martin, Lausanne University Hospital, Avenue Pierre Decker 4, 1011 Lausanne, Switzerland.
Email address: robin.martin@chuv.ch (R. Martin).

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However, it became more prevalent in the 1960's in Canada by Gariépy in Montreal (1964) and in the US by Coventry (1965) through his work at the Mayo Clinic.[1]

Around this period, there were early indications by surgeons that osteotomies would have a positive impact on cartilage repair. In 1959, Pridie presented a newly developed method for the treatment of osteoarthritic joint surfaces of the knee that he named subchondral drilling during the Congress of the British Orthopaedic Association. It was reported as a concise 11 lines publication in the Proceedings of the meeting, where Pridie mentioned that osteotomy to correct malalignment could be of additional benefit.[3] In the same manner, Steadman was later able to confirm the important role of osteotomy in his approach of bone marrow stimulation by microfracture.[4,5] He was able to show, with combined medial opening wedge high tibial osteotomy and microfracture, a 91% survivorship at 7 years in a large case series of 106 active patients with varus gonarthrosis.

Realignment osteotomy became a well-established treatment for unicompartmental knee osteoarthritis. In this indication, it proved long-term efficiency with survival rates of 91% at 5 to 8 years, 84% at 9 to 12 years and 70% at 12 years.[6-8] It was also shown to promote healing of the damaged articular cartilage on secondary arthoscopies.[9-11] Despite evidence of efficient operative care, the procedure was initially not highly implemented in practice,[12,13] which may have been due to reports of high incidences of complications associated with the procedure, including peroneal nerve palsy, hinge fracture, delayed union, nonunion, hardware failure and loss of correction.[14-16] Towards the end of the 20th century, surgeons adopted joint arthroplasty solutions for osteoarthritis (OA), and implemented isolated repair for the treatment of focal cartilage defects. However, over the last 15 years, literature reported lower risk of complications with osteotomies (7%), largely due to improvements in techniques, implants and control of potential risk factors.[17] This resulted in a renaissance of the procedure for unicompartmental OA of the knee.[18]

Parallel to this, cartilage restoration procedures have gained interest for the treatment of focal cartilage defects and among patients who desire an active lifestyle.[19] Besides the technique of bone marrow stimulation, different grafting procedures also became available but there is no consensus on a gold standard as each procedure may have limitations. Indeed, many studies have demonstrated short-term success rates of various cartilage repair procedures, but long-term durability remains a challenge. Mithoefer et al[20] have shown in their systematic review that microfracturing is related to deterioration of functional outcome scores in 47% to 80% after 2 years. Osteochondral autograft transfer can lead to a 55% failure rate at 10 years.[21] Autologous chondrocyte transplantation (ACI), the current technically most sophisticated and costly cartilage restoration procedure, is known to be associated with 25% of unsatisfied patients at 12 years.[22,23] Therefore, there remains high potential of improvement, as most patients presenting with cartilage defects are quite young. Among other reasons, there may be a strong association with relatively few of these procedures being performed in conjunction with realignment osteotomy.[24]

Despite the proven benefits of osteotomies creating a favorable biomechanical environment, the procedure is not standardized in cartilage repair. The Patient Registry report of 2018 ($n = 535$)[25] and 2020 ($n = 1945$)[26] of the International Cartilage Regeneration and Joint Preservation Society revealed concomitant osteotomy in all cartilage restorations procedures in only 1.5% and 1.7% of the cases, respectively. Importantly, differences for the implementation of osteotomy in patient care are observed worldwide. In 2019, an analysis of the German Cartilage Registry ($n = 4986$ patients) revealed combined osteotomy in 46% of cartilage repair procedure.[27] In 2014, Montgomery et al[28] analyzed US billing codes from 2004 to 2009 for 38,203 cartilage repair and restoration procedures. They reported that osteotomy was performed in conjunction with ACI in 6.3%, associated with osteochondral allograft in 4.5% and less than 1% in conjunction with microfractures and mosaicplasty. On the other hand, Growd et al[29] analyzed trends for the management of chondral lesions in the knee in the US between 2010 and 2016 and observed a linear increase in osteochondral autograft transplantation, osteochondral allograft transplantation, and autologous chondrocyte implantation. Overall, cartilage restoration procedures increased by 206%.

Surgeons appear to be seeking more for cartilage restoration techniques (osteochondral transplantation, ACI) and seem to lack or ignore information to optimize the biomechanical environment.[30] Because of this overall message, some geographic areas of the world may not provide surgical training with sufficient exposure and experience in the field of osteotomies. Suboptimal preparation of the incoming surgeons might lead to a further decline in practice of the procedure. Other factors could improve or dissuade the standard of osteotomies implicated in regular practice. Such as, in Germany, the increased trend correlated with changes in billing practices since correction of malalignment of more than 5° was required for reimbursement from insurance.[27,31]

This review will address why osteotomy remains the cornerstone in improving the long-term outcome of cartilage restoration procedures in the presence of overloaded knee joint compartments. Even with the advances in tissue engineering and orthoregeneration, realignment remains the most important prerequisite to assure durable stability.

From cartilage defect to OA: the capital role of biomechanics in the onset of an ongoing disease

In the European population, lower limb malalignment has a high prevalence. Nearly 50% of the individuals have a hip-knee-ankle (HKA) angle in varus >3° (32% male, 17% females) and almost 5% have valgus >3° (2.8% female, 2% male).[32]

For unicompartmental osteoarthritis, malalignment of the knee is known to promote both the initiation and the progression of OA, even for small mechanical axis deviations. The Multicenter Osteoarthritis Study[33,34] has shown in knees without any magnetic resonance imaging (MRI) evidence of cartilage damage at baseline that a varus ≥2° or a valgus >3° were associated with an increased risk of incident cartilage damage over the subsequent 30 months, in the medial (Odds Ratio 1.4/1° varus) or the lateral (Odds Ratio 1.8/1° valgus) compartment, respectively. Following the onset of OA, malalignment is a risk factor for disease progression.[35] In knees with OA staged Kellgren Lawrence ≥2, Sharma et al[36] reported that a varus ≥2° was associated with nearly 4-fold increase on the medial side, whereas a valgus ≥2° was associated with a nearly 5-fold increase towards the lateral compartment at 30 months. Cerejo et al[37] showed that the influence of malalignment on the risk of OA progression increases with the stage of the disease. Once

OA has developed, malalignment may permeate a vicious cycle of joint damage inducing further joint erosion, loss in cartilage thickness, collateral ligament distension, increased adduction/abduction moment of the knee, increased malalignment and therefore more overload and progression of OA.[33,38-41] Overloading could lead to poor vascularization by osseous hypertension[42] and to the suppression of chondrocyte metabolism with a reduction in collagen biosynthesis.[43]

In the onset and history of focal traumatic cartilage defects, mechanics might play also a central role. First, there is a significant correlation between malalignment and defect location.[44] Second, although the natural history of cartilage defects is not completely understood, these lesions might progress into OA.[45] This most probably results due to the contact pressure concentrating around the rims of cartilage defects, which will be increased by additional malalignment.[39]

In this ongoing process, there is not always a clear demarcation between focal traumatic defects and early OA. Isolated cartilage defects can cause pain and disability comparable to that of severe OA.[46] In many studies, there is no reliable difference between patients with focal cartilage defects and early osteoarthritis. Since cartilage restoration procedures appear to be increasing in popularity and are being performed more frequently for older patients, both entities will merge in an increasing number of cases. This is important since osteoarthritis is still the most relevant contra-indication for any type of cartilage repair. If the isolated cartilage lesion is indeed a potential precursor of OA, it would be even more of interest to look at every traumatic cartilage defect as a major insult to the joint with a potential chance of a possible transition to unicompartmental OA.[45] Therefore, cartilage surgeons should show by their act that in their patients they want to avoid or delay such an evolution and postpone later prosthetic surgery. Treatment algorithms of cartilage defects should highlight a normalization of the mechanical load conditions to improve the homeostasis surrounding the entire “organ” and influence long-term survival.

Breaking the vicious cycle to avoid failure

The goals of treatment for patients with symptomatic articular cartilage lesions in the knee joint are to provide pain relief and ultimately to delay and/or prevent the development of secondary degenerative disease. To break this vicious cycle, realignment osteotomies are of paramount importance in the treatment of focal traumatic cartilage defects. The concept is to address both the underlying pathology and the cartilage lesion. The aim of osteotomy is to redistribute the load applied to the knee joint, reduce the adduction/abduction moment of the knee, increase joint space width and decrease load[47] as well as peak pressure.[39,40] This is well documented on the medial side with varus deformity but less so for the lateral side with valgus deformity.

Osteotomy was developed to decrease pressure of the cartilage in order to reduce pain and to slow down the degenerative process. In advanced grade IV Outerbridge defects, which correspond to a complete erosion of cartilage with exposure of the subchondral bone, this mechanism of action of osteotomy is more questionable. However, Floerkemeier et al[48] have shown that the amount of pain improvement with osteotomy is not influenced by the stage of cartilage damage. Osteotomy remains efficient on the entire spectrum of the disease, even when focal defects lead to subchondral bone changes and adjacent early OA. On the other hand, cartilage repair has shown important limits of benefit in advanced chronic defects with adjacent OA and subchondral bone changes, such as thickening of the subchondral bone, formation of subchondral cysts and intralesional osteophytes.[49,50] Leg axis correction could then be of particular importance in these chronic advanced defects. The treatment algorithm could be adapted to first perform the osteotomy in order to restore joint mechanics, and then a secondary articular cartilage restoration if needed.

With standardized “adjuvant” leg axis correction, an improvement in long-term survival rates of various cartilage restoration procedures was reported. For ACI, Minas et al[22] have observed a survival increase from 66% to 88% at 15 years and concluded that, given the economic challenges of ACI, it would be advisable to consider high tibial osteotomy (HTO) to provide the most durable long-term outcome. Similarly, Bode et al,[51] in a nonrandomized controlled clinical trial, determined higher graft survival rates at 6 years in patients who received combined ACI with high tibial osteotomy (89.5%) compared to patients treated by ACI alone (58.3%). With osteochondral allograft transplantation, A.E. Gross group[52] analyzed 99 knees at a mean of 7.5 years and described significantly higher failures in malaligned knees (7 failures in 14 cases) than in well-aligned knees (14 failures in 85 cases). More recently, Sochacki et al[53] have shown a reduction risk of reoperation (OR: 0.2) in both ACI and osteochondral allograft transplantation when combined with concomitant osteotomy. Literature regarding comparative studies on the potential benefit of osteotomy on mosaicplasty or autologous matrix-induced chondrogenesis is lacking. In 2013, Minzlaff et al[54] reported in a noncomparative study, successful treatment of deep osteochondral defects of the medial femoral condyle and concomitant varus malalignment by combined mosaicplasty and high tibial osteotomy. They reported 90.1% graft survival rate at 8.5 years after surgery in 74 patients. Similarly, Kaiser et al.[55] have shown in a retrospective case series of 18 condylar lesions treated with autologous matrix-induced chondrogenesis that clinical results remained stable up to 10 years after surgery in the well-aligned knee with 66% of their cases receiving realignment osteotomy.

Systematic screening for malalignment should be mandatory: even small deformities require correction before or together with cartilage repair!

Every patient who receives cartilage repair should have a standing hip to ankle radiograph in the pre-operative assessment. For the most part, alignment is still assessed by clinical observation only for cases undergoing cartilage procedure (44% of cases in the German cartilage Registry, 2017, Spahn et al[44]). Historically, in the field of cartilage repair, deformities of more than 5° were seen as an indication for correction.[4] However, this 5° cutoff was apparently arbitrarily chosen without any scientific evidence. The limit most likely should be lowered with all the clinical evidence taken into consideration and the increased improvements for surgical accuracy of knee osteotomy. Such advancements providing more accurate corrections include preoperative digital radiologic measurements with templates, open wedge approaches with gap measurement, additional computer navigation, and stable fixation methods.[56,57] Higher accuracy of knee osteotomy allows to perform smaller correction and thus to address smaller deformities.

In 2011, Salzmann et al[58] reported that 48.3% of expert surgeons in the German-speaking Society of Arthroscopy were still only performing corrections for deformities of >5° for cartilage repair, while 30.6% were already considering an osteotomy for deformities at 3° or 4°, and 9.8% at 1° or 2° In 2020, an analysis of the German Cartilage Registry has confirmed this trend towards conducting additional osteotomy in smaller deformities, with more than 50% of the surgeons performing a correction in malalignment greater than 3°[27] A current break point for concomitant realignment osteotomy at 3° was also supported by Niemeyer et al[59] who had shown the benefits of medial open wedge osteotomy for medial OA beyond an HKA angle of 3° More recently, Bode et al[51] have shown superiority of combined HTO and ACI versus ACI alone in a cohort of patients with mild varus deformity between 2° and 4° of varus. At a mean follow up of 6 years, they reported a graft survival rate of 89.5% in the combined treatment group based on MRI findings and the need for revision surgery (compared to 58.3% in the ACI alone group). With regard to osteochondral allografts, a same trend was also seen, where residual malalignment was identified as a predictor for failure.[60,61] Leon et al[61] reported that persistent postoperative malalignment occurred more frequently in failed allografts. Gross et al[62] recommended that any degrees of deformity toward the diseased compartment was an indication for osteotomy. When the osteotomy and transplant involved the same side of the joint, the osteotomy was shown to be performed at least 2 cm away from the interface between the graft and the host, and this was related to the concern that the osteotomy could jeopardize the blood supply to the graft.[61,63,64]

However, the amount of correction remains a source of debate and has evolved over time. In 1979, in the treatment of medial unicompartmental OA, Fujisawa et al[65] suggested an ideal correction to align the mechanical axis to pass through a point at 30% to 40% of the lateral plateau width, with a reference of 0% at the midpoint of the tibial eminences and at 100% on the external edge of the lateral plateau. In 1987, Hernigou et al[66] suggested that the weight bearing line be adjusted from 3° to 6° of valgus. In 1989, Miniaci et al[67] proposed a geometrical planning method in order to attain precise degrees of the angle correction. In 1992, Dugdale et al[68] proposed an ideal correction that would bring the mechanical axis between 62% and 66% of the metaphyseal width, related to the medial border at 0%. Later, an individualized approach was introduced, based on the severity of OA and the extent of OA to the opposite compartment,[69] while other surgeons (Marti et al[70]) directed the amount of correction with relation to severity of cartilage damage in the compartment to be unloaded. For osteotomies performed as an adjuvant to cartilage repair, the optimal amount of correction has not been established. Some surgeons suggest that neutral alignment of the knee, a so-called *Morphotype Correction,* may be the ideal scenario for ACI cartilage maturation, whereas others have suggested applying the same principles as for OA.[71,72] For osteochondral allograft transplantation, Bugbee suggests a threshold for performing realignment osteotomy of 3° with an aim to normalize the alignment. He proposes overcorrection in a situation where adjacent compartment degenerative disease exists.[63,64]

Further surgical evolution: trending towards borderline indication osteotomy

Decisions when to perform leg axis correction for an HKA angle of less than 3° is still a source of debate but is gaining increasing interest, which most likely will be an individualized decision. In our experience, we would consider lowering the threshold below 3° under the following criteria:

1. When the focal defect affects the medial side. The contact pressure is equally distributed between the medial and lateral joint line for alignments in slight valgus (up to 4°).[39] In a neutrally aligned leg, the medial compartment supports up to 60% of the load.[40,47] With varus deformities, contact pressure rapidly increases on the medial side and it approaches 75% of bodyweight for one degree of varus alignment and up to 80–90% of the entire pressure for varus deformities of only 3° to 5°[73] We would thus recommend correcting varus deformities below 3° for cartilage repair in the medial compartment.
2. If the focal defect is at increased risk of failure for cartilage restoration:
   A. Larger defects (Fig. 1). We would consider >4 cm^2 as a threshold. Defect size has historically been used as a critical element for management of chondral defects in the knee. Most algorithms use 2 cm^2 as the threshold between marrow stimulation techniques and osteochondral autograft vs cartilage restoration by ACI and osteochondral allograft.[74] This threshold could be questioned because microfracture[75,76] and mosaicplasty[77] have been reported successful when applied for defects up to 3 to 4 cm^2 in some studies, where the risk of failure increases. Long-term ACI studies have shown lesion size above 4.5 cm^2 as a risk factor for failure.[78] In the medial compartment, Bode et al[51] have shown an ACI survival improvement when it is combined with HTO for treatment of large medial femoral condyle defects (mean size 4.6 cm^2) in small deformities (mean varus 2.8°). Similarly, failed osteochondral allografts are associated with defect sizes above 5 cm^2.[79]
   This threshold value of 4 cm^2 could probably be adjusted with respect to the size of the knee and the laterality of the lesion. Current treatment algorithms utilize only the absolute defect size. Ratio of defect size to condylar size or relation to laterality have been reported but need further investigation.[79] Flanigan et al[80] have shown in a bovine model that subchondral bone contact would increase more rapidly with defect size in the lateral than the medial compartment.
   B. Chronic defects (more than 2 years) with poorly delineated margins, and/or subchondral bone changes and/or adjacent early OA, leading to join space narrowing of joint line.[27,81]
   C. Partially resected adjacent meniscus.[27]
   D. Overweight.[27]
   E. Female gender.[81,82]
3. Revision cartilage repair[27,83] (Fig. 2).
4. Asymmetry. When the lower limb is malaligned in comparison to the opposite lower limb (symmetrizing osteotomy) (Fig. 3).

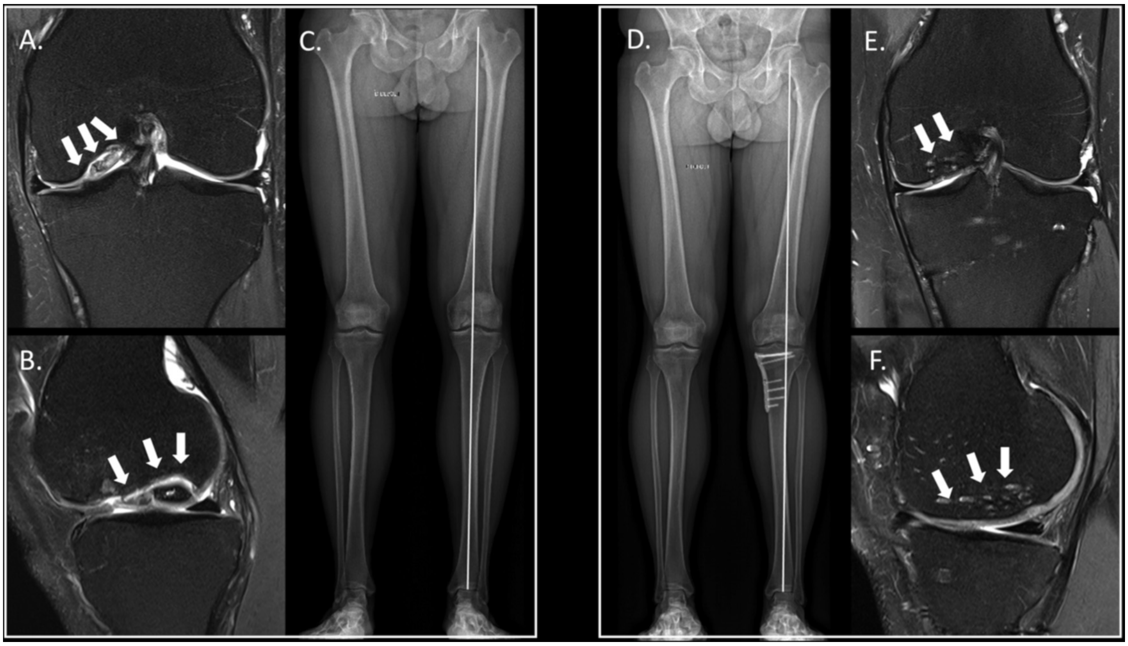

Fig. 1. Push towards borderline indication osteotomy. Large and/or uncontained defects. **A-C**, osteochondritis dissecans of the medial femoral condyle in the left knee of a 35 years old male: large (6 cm^2) uncontained defect (white arrows). Left lower limb offers a hip-knee-ankle (HKA) angle of 1.5º in varus. **D**, **E**, and **F**, patient received high tibial osteotomy and the "sandwich" technique with autologous bone grafting and autologous chondrocyte implantation (ACI). Good clinical and imagery outcome at 2 years. MRIs in T2 fat sat weighted images.

Potential of osteotomy alone to suffice for focal cartilage defects

Osteotomy allows the affected compartment to be unloaded. Several studies have assessed on second look arthroscopy that this alone might lead to fibrocartilage regeneration and this might question the need for an additional cartilage repair procedure.[9-11,84] However, the respective contribution of the cartilage versus the osteotomy procedure to the overall outcome could also have patient variability and thus remain controversial.

Many studies have focused on OA treated by osteotomy with or without cartilage procedures. Kim et al,[85] in second look arthroscopy, have shown that osteotomy alone was associated with the appearance of cartilage regeneration, both in the medial femoral condyle (51.9%) and tibial plateau (34.6%). Correlation between cartilage regeneration and clinical and radiographic results after HTO may still be debated. Jung et al,[86] in a nonrandomized retrospective study, analyzed the effect of subchondral bone drilling of bare surfaces among patients with osteotomy and found no difference at 2 years in the clinical outcome and for the formation of fibrocartilage with or without subchondral drilling. Similarly, Lee et al,[87] confirmed in a second look arthroscopy retrospective study that microfractures of the medial femoral condyle during open wedge HTO produced filling of the degenerative cartilage defect but did not improve clinical scores and magnetic resonance observation of cartilage repair tissue (MOCART) score at 2 years. Pascale et al[88] reported higher patient satisfaction but similar clinical scores in patients receiving microfractures with HTO compared to HTO alone. A systematic review by Filardo et al[89] in 2018 found no evidence for combining cartilage treatment and knee osteotomy in OA joints. Thus, for unicompartmental OA, osteotomy could be a stand-alone surgery. The question of the potential benefit of adding a cartilage procedure remains open.

For focal cartilage defects, there are few comparative studies on osteotomy with vs. without cartilage repair. Based on the German Cartilage Registry, Faber et al[83] reported that concomitant osteotomy results in better postoperative KOOS values, lower pain levels, and a higher patient satisfaction when combined with cartilage repair. The systematic review of 2020 by Nimkingratana et al[90] concluded that when osteotomy was associated with cartilage procedures, increased rates of repairs and shorter periods to return to work were seen. For focal cartilage defects, osteotomy could therefore act as a solid foundation for the reconstruction of the lesion.

Tibio femoral joint experience: a key improving cartilage repair of the patello femoral joint

The patello-femoral (PF) compartment is the most frequent location of focal cartilage defects. Widuchowski et al[91] reported a 60% incidence of PF lesions in a series of more than 25,000 knee arthroscopies performed in patients with a mean age of 39 years who presented with knee pain due to a variety of etiologies. Of the lesions reported, 82% were patellar and 18% were trochlear. When performing x-rays in patients ≥50 years of age with knee pain, Ducan et al[92] diagnosed 64% with cartilage lesion in the PF joint.

Similar to tibio-femoral (TF) cartilage defects, osseous malalignment plays a central role in onset and progression of chondral damage in the PF joint. Both overloading and instability are involved in the initiation, location and progression of PF chondral

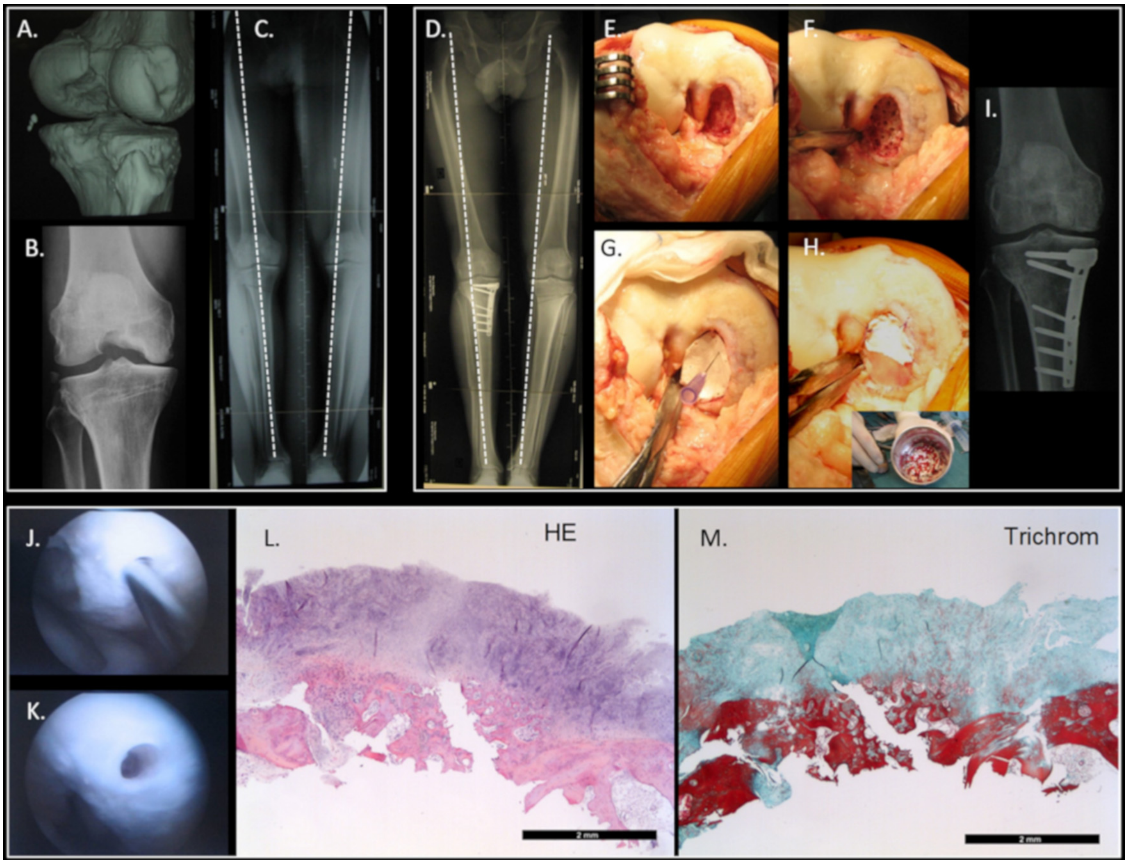

Fig. 2. Push towards borderline indication osteotomy. Revision surgery case. Osteochondritis dissecans (OCD) of the medial femoral condyle with varus malalignment in the right knee of a 46 years old mountain farmer. He was referred for remaining pain after primary surgical treatment by arthroscopic fragments removal plus a closing wedge type corrective high tibial osteotomy (HTO). **A-D**, Failure of primary surgery. **A**, Computed Tomography with 3D reconstructions. Posterior view showing persistence of a defect involving 50% of the carrying surface of the medial condyle. **B**, Tunnel view at 45° depicting the limited remaining medial condyle in flexion. **C**, Standing hip to ankle radiograph showing that osteotomy was probably insufficient as it corrected the alignment to neutral only. **D-I**, Revision surgery. **D**, Further open wedge HTO correction of 4° to place the mechanical axis on 35% lateral (Fujisawa Point) fixed by medially place Tomofix plate. **E** and **F**, Debridement of OCD ground by removal of the sclerosis and deep cancellous bone drilling. **G**, preparation and suturing of a type I/III resorbable collagen membrane (Chondro-Gide, Geistlich Pharma AG) on the uncontained defect. **H**, complete filling of defect with 1:1 mixture of granules of hydroxyapatite granules (Orthoss, Geistlich Pharma AG) and cancellous bone retrieved from the supracondylar area. Finalizing the suturing of the Matrix allowing reshaping condylar convexity. **I**, Postoperative standing AP radiograph at 6 years showing the filled up area of the medial condyle and the maintained joint line. Patient still working as mountain farmer. **J-M**, At 13 months: removal of osteotomy plate and control arthroscopy plus biopsy. **J** and **K**: Arthroscopy confirming the restored medial condyle and the substantial thickness of the cartilage regenerate. Biopsy performed in the original defect. **L** and **M**, Histology with hematoxylin and eosin (HE) and Masson's trichrome staining shows newly formed bone and fibrocartilage coverage with hyaline like areas.

pathology in 96% of patients, as reported by Namora et al[93] They lead to repetitive microtrauma of the chondral surface resulting in fissures and/or fibrillation which affect predominantly the lateral part of the PF joint.[94] Instability might additionally lead to patellar dislocation, which is potentially associated with a shear lesion of the chondral or osteochondral unit in up to 95% of patients.[95] Typically, this macrotrauma affects the distal-medial portion of the patella and the proximal lateral part of the trochlea.

Once the PF lesion is initiated, a vicious cycle begins which resembles that of the TF joint. With PF overload, the lesion progresses to erosion associated with secondary medial patellofemoral complex insufficiency, lateral retinaculum contracture and chronic patellar subluxation. This entire scenario thus leads to further increase in lateral contact pressure and wear which is favored by the higher contact pressure in PF joint, having a range from 3 times total body weight during stair climbing and up to 20 times total body weight following jumping action.[96,97]

Osseous PF malalignment is more complex than in the TF joint. In the TF joint, overload is predominantly related to the frontal malalignment only and the decision of correction is directly based on precise degrees of deviation in a single plane. In the PF joint, many biomechanical factors may influence the distribution of patellofemoral contact forces, not only in the frontal plane, but also in the sagittal and transverse planes. These factors could be more closely related with the initiation of patellar than trochlear defects.[98] The contribution of each factor to the total increase of lateral PF joint pressure and instability remains to be determined. Furthermore, for some of these factors, precise cut off values for correction remain a source of controversy. This makes the decision to determine

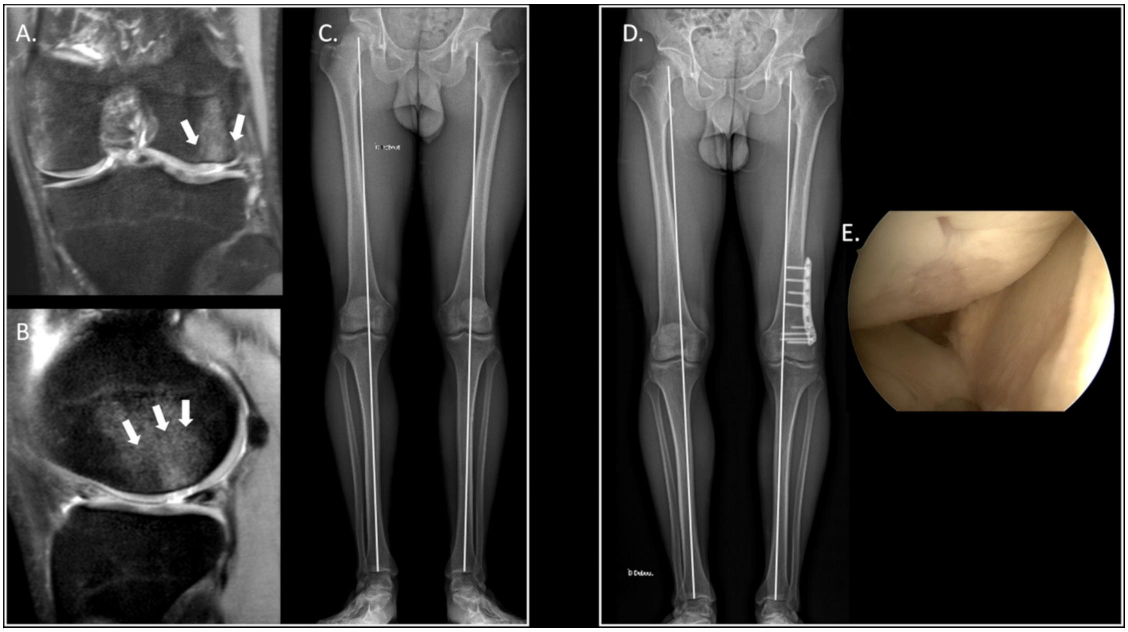

Fig. 3. Push towards borderline indication osteotomy. Asymmetry. **A-C**, Full-thickness articular cartilage defect (2 cm^2) of the lateral femoral condyle in the left knee of a 21 years old male. Left lower limb is well aligned, whereas the right lower limb offers a hip-knee-ankle (HKA) angle of 2.5º in varus. **D** and **E**, patient received lateral open wedge distal femoral osteotomy for symmetrizing HKA angle, combined with arthroscopic microfractures of the defect.

the best course of treatment difficult along with outlining the importance to improve our biomechanical knowledge of the PF joint. For ease of understanding, we could classify these biomechanical factors into Extraarticular and Intraarticular,[99] where Extraarticular factors include valgus malalignment[100] in the coronal plane and torsional deformities in the transverse plane. Increase in femoral anterversion[101-103] and in external tibial torsion[104] have all been associated with patellar maltracking and instability. Intraarticular factors for PF malalignment would include:

1. Frontal plane: increased tibial tubercle–trochlear groove (TT-TG distance). This could be associated to a lateralization of the tibial tubercle, or a medialized trochlear groove related to trochlear dysplasia. Recent literature has suggested that patients with a distance greater than 17 mm might benefit from realignment.[105] The tibial tubercle–posterior cruciate ligament distance was proposed as an alternative to the TT-TG, but describes pure lateralization of the tibial tubercle without the trochlear counterpart.[106] This measurement can be helpful to assess coronal plane malalignment in cases of extreme trochlea dysplasia (eg, Dejour B/barrel shaped) and clarifiy if distal realignment surgery should be considered.
2. Sagittal: patella alta, which is characterized by a Caton-Deschamps index above 1.2. This condition will postpone engagement into the trochlea groove and therefore increase contact pressure on the distal patella and the proximal portion of the trochlea. Ambra et al[98] reported that patella alta is found in one fourth of patients with cartilage defects in the PF joint. One quarter of the patients with patellar instability have patella alta.[107] The Sagittal Patellofemoral Engagement index is supplementary tool to evaluate patellar height on MRI saggital images with the knee in full extension. It helps to indentify cases where inadequate engagement is present in the absence of an increased Caton-Deschamps index on x-rays. The index is a ratio between the length of trochlear cartilage in which the patella has already engaded and the entire length of the patellar cartilage. A Sagittal Patellofemoral Engagement <0.4 is considered as insufficient functional PF engagement.[108]
3. Congruency: Trochlear dysplasia will add incongruity and predispose to further lateral subluxation of the patella. It is found in more than one third of the patients with focal cartilage lesions in the PF joint.[98]
4. Insufficiency of the medial patellofemoral complex. This complex acts as the main restraint to lateral patellar translation, and consists of two portions: the medial patellofemoral ligament and the medial quadriceps tendon femoral ligament.[109] The patellar tilt represents the inclination of the patella relative to the horizontal line tangent to the posterior condyles. An increased tilt (>5°) was used to report PF instability in the 80's but it was later shown that it could result not only form medial patellofemoral ligament insufficiency but also from PF dysplasia, increased TT-TG distance or patella alta. It has lost his previous role within the treatment algorithm of patella instability as it may also occur without patellar subluxation/dislocation.[110]

Failure rates of cartilage repair with long-term consequences were historically more apparent in the PF compartment. Brittberg et al initially reported good results of ACI in the PF joint in less than 30% of cases in their original publication of 1994, where he recognized that "*The correction of underlying joint abnormalities concomitantly with the transplantation of chondrocytes may improve the success rate for patients with patellar defects.*"[111] Subsequent studies, revealed improved outcomes for concurrent tibial tubercle osteotomy, which nearly matched outcomes in the femur.[88,112-116] Gomoll et al.[114] reported that ACI for cartilage defects in the

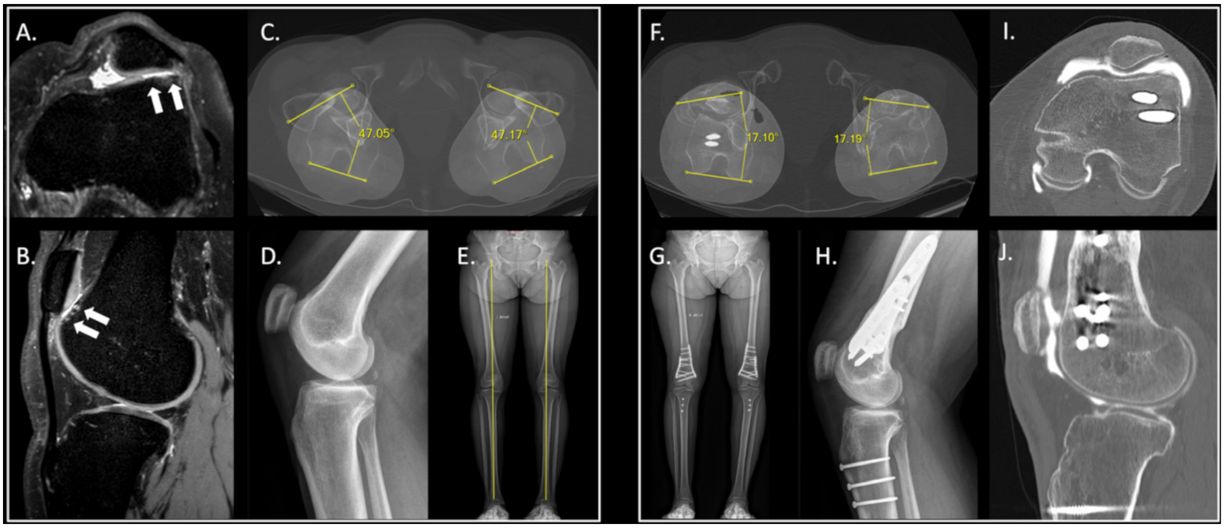

Fig. 4. Unloading the patellofemoral compartment. **A** and **B**, Full-thickness articular cartilage defect (white arrows) on the most proximal and lateral part of the trochlea in a 39 years old female (2.2 cm^2). History of patellar dislocation. Bilateral involvement. Complete illustration in this figure for the left knee only. **C-E**, Full radiologic malalignment screening: increased femoral anteversion (47^0) and TT-TG distance (25 mm) on CT, patella alta (Caton-Dechamps index: 1.25) on knee x-rays and well aligned lower limbs on the standing hip to ankle radiograph. **F-H**, Patient received derotational femoral osteotomy, tibial tuberosity osteotomy with concomitant distalization and medialization, medial patella femoral ligament reconstruction and an AMIC procedure on the defect. Postoperative radiologic work-up: normal range femoral anteversion (17^0) and TT-TG (15 mm), corrected patellar height (Caton-Dechamps index: 1), and slight varus deviation on the standing hip to ankle radiograph. **I** and **J**, CT arthrogram of the knee shows healing of the defect with adequate sagittal patella engagement index at 0.3.

patella with concurrent anteromedialization or anteriorization without medialization in cases of normal preoperative TT-TG offered good to excellent results in 80% of patients at 4 years. In a comparative study, Henderson and Lavigne[113] reported that patients treated with ACI had better outcomes if they also underwent TTO at an average follow-up of 2 years. In 2017, Trinh et al[117] presented a systematic review to compare the clinical outcomes of patients with patellofemoral chondral defects undergoing isolated ACI vs ACI and concomitant distal realignment (anteriorization, medialization, or anteromedialization). Eleven studies were included and showed significantly greater improvements of combined ACI and osteotomy versus isolated ACI. Progressively, anteromedialization TTO became the most commonly used realignment procedure in the treatment of PF cartilage defects.

However, durability of cartilage repair in the field of the PF joint remains a challenge. For ACI, survival rates at 10 years of 60% to 70% were reported for the PF whereas survival of 80% has been reported in the TF joint.[22,23] The key to an improved long-term success in the treatment of PF cartilage defects could be a more comprehensive and individualized approach. The treatment strategy should be based on an evolution of the “à la carte menu” introduced by Dejour[118] for patellar instability, which aimed at correcting any of the existing predisposing factors. Malalignment should be explored more accurately, not only in the frontal plane for TT-TG measurement, but also in the sagittal and transverse planes.

Before any cartilage procedures in the PF joint, comprehensive diagnostic imaging should be considered, including standing long-leg radiographs for coronal alignment, knee x-rays with lateral and Merchant view for patellar height and tilt measurement and a CT scan (or MRI) with superposition of images through the knee, hip, and ankle for measures of femoral torsion. Torsional deformities often remain undetected for the condition of patello-femoral malalignment and are therefore not addressed by treatment.

An individualized treatment algorithm[99] should be implemented where all the identified contributing factors can be addressed. The goal of these procedures is to restore a stable PF joint—to prevent recurrence of patellar instability—and to unload the area involved in the defect. We suggest addressing the following considerations:

1. Extra articular first: frontal and/or axial realignment (Fig. 4).

Femoral varisation osteotomy in cases of valgus deformities was shown to improve patellar imbalance. We suggest the correction of any deformity above 3°.[100,119,120] Lee et al[102] have shown in a cadaver study that increased internal femoral torsion caused greater contact pressure on the lateral facet of the patella. There is increasing evidence that external femoral derotational osteotomy may improve patellar malalignment in cases of increased femoral anteversion.[103] We therefore suggest correcting internal torsion above a threshold value of 30°.[101] Combined valgus and internal torsion deformity are addressed by simultaneous biplanar varisation and torsional femoral osteotomy.[121]

2. Intraarticular realignment: not only distal (Fig. 5).

The importance of anteromedialization TTO for improving the outcomes of ACI in the PFJ was acknowledged in many studies but mostly in the US. TTO should be adapted to the location of the lesion in the patellofemoral joint, the TT-TG and patellar height. It

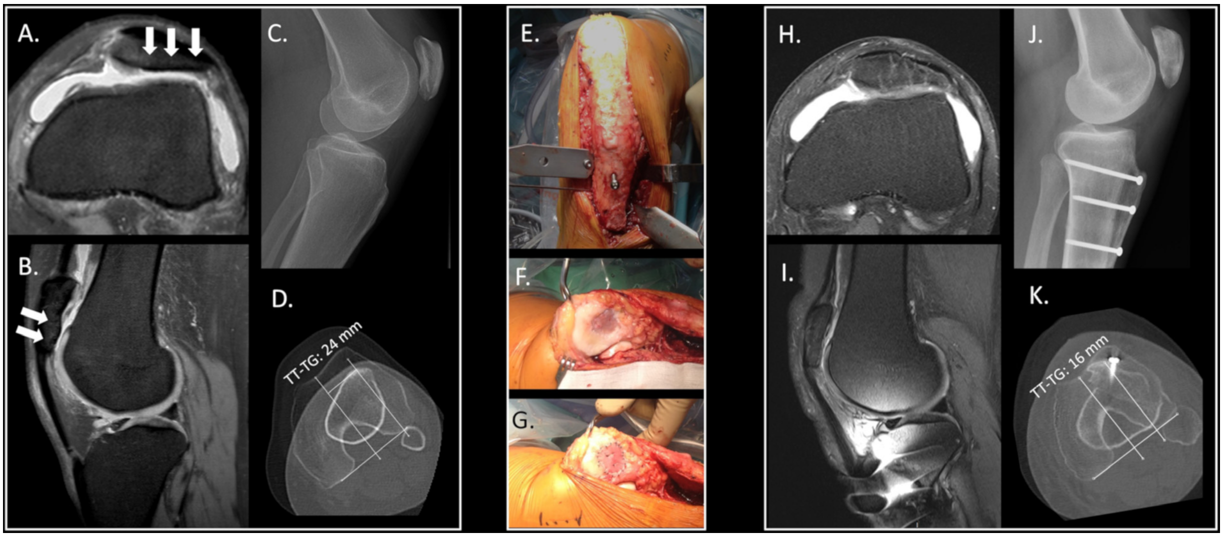

Fig. 5. Unloading the patellofemoral compartment. **A-D**, Lateral distal patellar full-thickness articular cartilage defect in a 35 years old female (3.5 cm^2). Biomechanical environment: tibial-tuberosity to trochlear groove distance (TT-TG) of 24 mm combined with patella alta (Caton-Deschamps index at 1.3). **E-G**, patient received tibial tuberosity osteotomy for anteromedialization and distalization, combined with autologous matrix-induced chondrogenesis (AMIC). **H-K**, Postoperative outcome at 2 years. MRIs in T2 fat sat weighted images.

should be combined with a reconstruction or repair of the medial patellofemoral complex and, if needed, with proximal realignment by trochleoplasty and lateral reticular lengthening.

Both anteriorization (Maquet, 1963[122]) and anteromedialization (Fulkerson, 1983[123]) TTO are powerful tools to decrease mean patellofemoral compartment pressures distally throughout flexion.[124-126] By changing the angle of the osteotomy cut, one can customize the procedure to include more medialization for instability cases or more anteriorization for cartilaginous unloading guideline. Anteromedialization decreases the mean total contact pressure, and particularly for lateral trochlear and lateral/distal patellar defects. Therefore, it would be a counter-indication for treatment of lesions of the proximal medial portion of the patella and the central groove of the trochlea.[94,127]

Distalization TTO remains a controversial procedure, as it would theoretically increase patellofemoral contact pressure in flexion.[128] However, when performed to correct patella alta, clinical studies have shown that it improves patellar stability and reduces anterior knee pain by favoring the earlier engagement of the patella in the trochlea during early knee flexion.[107,129,130] Furthermore, a systematic review by Magnusen et al[131] did not identify an increased risk of PF OA at 5 to 10 years of follow-up.

Deepening trochleoplasty was described to improve intraarticular congruency and should be considered to control patellar instability in high-grade dysplasia (Dejour types B and D). Additionally, it could reduce the PF contact pressure by an improvement of the contact area. However, whether trochlear dysplasia has an influence on the outcome of patellar cartilage procedure remains a source of controversy. Mehl et al[132] reported poorer outcome for patients receiving ACI with major trochlea dysplasia at a mean follow up of 6.5 years, whereas Barbieri Mestriner et al[133] showed favorable outcomes of ACI even in patients with high-grade trochlear dysplasia.

Conclusion

Cartilage surgeries are complex, time consuming and associated with high impact on health economics. Therefore, it is important to include an overall assessment and to recognize the necessity to unload the affected ompartement with an axial realignment osteotomy. However, the truth and reality are different which we are forced to face. Depending on experience and skills of surgeon, the inhibition threshold to add a simultaneous osteotomy can still be particularly high. This inhibition might even be higher with more complex ACI procedures than with simple single stage bone marrow stimulation techniques. Therefore, staging should be considered if needed. Indications would first be to perform an osteotomy, then 6 to 12 weeks later continue with the cartilage procedure.

Today, among cartilage surgeons, axial studies and osteotomy need to progress into the stage of highest priority. If this narrative review has stimulated the thinking on surgical indications of osteotomy in cartilage repair, it has hopefully fulfilled his task.

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Animal welfare statement

We confirm that the submitted manuscript research was conducted according to the ethics relating to the use of animals in scientific work.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

RPJ conceived the idea, prepared the literature research and edited the manuscript. RM undertook additional literature searches, prepared the manuscript, created the figures and finalized the manuscript.

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