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Systematic Review

Anterior cruciate ligament allografts and low-dose gamma irradiation: a systematic review

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ABSTRACT

Anterior cruciate ligament (ACL) rupture is a common injury requiring surgical reconstruction in active patients. Autografts are considered the gold standard due to superior early biomechanical performance, but allografts offer advantages such as reduced operative time and elimination of donor-site morbidity. Irradiation is the primary sterilisation method; however, high doses impair mechanical integrity. Low-dose irradiation has been proposed to preserve graft strength while ensuring sterility. A systematic review was performed using EMBASE, PubMed and Scopus, supplemented with backward snowballing. Cohort and randomised studies comparing low-dose irradiated allografts to autografts in vivo were included. Primary outcomes were graft failure/revision rates, knee laxity (KT-1000/2000, Lachman, pivot shift) and patient-reported measures (IKDC, Lysholm). Eight studies comprising over 10,000 patients were included. Autografts demonstrated lower graft failure rates in younger (<22 years) patients, with revision rates of 10.1% for allografts vs. 2.9% for autografts. In older cohorts, outcomes were largely equivalent. Arthrometric testing showed greater knee laxity with allografts, but this did not consistently translate into differences in patient-reported outcomes. Return-to-sport was faster with autografts, reflecting earlier graft incorporation, while long-term outcomes converged once allografts remodelled. Autografts remain the graft of choice for younger, high-demand patients due to superior early stability and lower revision rates. Low-dose irradiated allografts may represent a viable alternative in older or less active populations. High-quality, prospective studies with standardised protocols are required to clarify long-term efficacy and guide graft selection.

Keywords: ACL, Allograft, Gamma radiation, Low-dose

INTRODUCTION

Anatomy and micro-anatomy of anterior cruciate ligament

The ACL is a key stabilizer of the knee joint, resisting anterior tibial translation and rotational loads.[1,2] Structurally, it comprises an anteromedial (AM) and a posterolateral (PL) bundle, with functional variation across the flexion-extension range.[3] The ACL is predominantly made of type I collagen, with regional specialisation in collagen type and proteoglycan content aiding in its viscoelastic and load-bearing properties as seen in Table 1.[4] Its hierarchical microstructure, including crimped collagen fibrils and fascicles within vascularized connective tissue, enables it to deform under stress and protect the joint.[5] Injury disrupts this architecture, with restoration of crimp structure being critical for functional recovery.[6]

Anterior cruciate ligament injury and grafts

ACL rupture is the most common knee ligament injury, with an incidence of 14 per 100,000 annually in the UK,

rising sharply among athletes.[9,10] Surgical reconstruction is typically indicated for active patients with full ruptures or symptomatic instability. Graft choices include autografts, bone–patellar tendon–bone (BPTB), hamstring or quadriceps tendon and allografts from cadaveric tissue.[11] Autografts are commonly used but may result in harvest-site morbidity.[12] The incidence of anterior knee pain is influenced by patient characteristics and rehabilitation as well as the type of graft.[13] Surgically, grafts are fixed in bone tunnels drilled in the femur and tibia, with fixation achieved via interference screws, cortical suspensory devices or cross-pins depending on graft type and surgeon preference. Anatomical single-bundle and double-bundle reconstructions are both practiced, the latter aiming to replicate native AM and PL bundle functions more closely albeit double-bundle reconstructions are quoted in the literature to be less than 2% of all reconstructions.[14] Allografts are typically reserved for older, multi-revision patients to avoid extended surgical time and harvest complications or younger athletes whose performance may be impacted by harvest-site morbidity.[15,16]

Graft healing proceeds through inflammation, revascularization and remodeling. In bone-including grafts like BPTB, healing occurs via bone ingrowth at the graft–bone interface.[17] In contrast, soft-tissue grafts require fibrovascular integration, a slower process influenced by graft type and mechanical loading. Despite surgical advances, there is a lack of consensus on evidence-based post-operative timelines for healing and return to sport.[18] Outcomes are evaluated via stability tests (Lachman, pivot shift, KT-1000), graft failure rates and validated patient-reported outcome measures. According to these outcomes, autografts appear to have marginally better outcomes compared to allografts although the clinical significance of this is debatable.[19]

Anterior cruciate ligament allografts

Allografts are typically sterilized with irradiation and ethylene glycol in order to prevent disease transmission or an immune response by the graft-receiving patient. Although allografts offer shorter operative times, faster recovery and no risk of donor-site morbidity, there are questions over their functional suitability after this sterilization. Conrad et al found that irradiated tendons had lower load to failure, lower stiffness and lower Young's Modulus when compared to non-irradiated 'control' tendons in an in-vitro study.[20] A 2013 meta-analysis of prospective studies also found that allografts were associated with higher rates of graft failure than autografts although functional outcomes in non-failure cases were similar.[21]

This suggests a link between allograft sterilisation and their observed loss of mechanical capabilities. Haut and Powlison (1990) has shown that irradiation can reduce the mechanical strength of collagen by cleaving its peptide bonds along the polypeptide chain, although historically 3-4 Mrad of radiation were typically used. The disruption of these peptide bonds will result in lower tensile strength and lower load to failure.[22] The extent of disruption to the collagen peptide bonds is dose-dependent.[23]

Nonirradiated ACL allografts have shown no significant differences to autografts in 'functional outcomes', including levels of activity, stiffness and pain.[24] However, they are not first line due to increased infection risk from the absence of irradiation sterilisation.[25] Although the rates of infection after ACL repair are reportedly low, severe complications such as septic arthritis support use of precautions. Preventing infection avoids delayed return to activity, graft removal and revision surgery, as well as inferior functional long-term outcomes.[26] Irradiated allografts have been associated with compromised mechanical stability and loss of tensile strength in ex- vivo studies involving both ovine and human models.[27,28] Low-temperature, low dose gamma irradiation can inactivate enveloped and nonenveloped DNA and RNA, allowing for effective sterilisation whilst partially preserving the mechanical properties of the allograft and as such have been selected as the focus for this review.[29]

Tejwani et al, retrospectively reported graft failure rates of ACL reconstructions performed with different dosage irradiated allografts (Table 2).[30] A dose-dependent relationship was established between revision rates of allografts and irradiation sterilisation. Furthermore, no differences were found between soft tissue grafts such as tibialis posterior or hamstring tendons and BPTB grafts. In the case of non-irradiated patellar tendon allografts, there is insufficient evidence to suggest that mechanically, they are inferior to BPTB autografts.[21,31] Thus, leading to the consideration of low dose irradiation for sterilisation as a method of preserving the biomechanical properties of the graft; reducing the risk of graft failure in allografts. It is hypothesized that use of low-dose gamma irradiation for allografts can produce the same mechanical outcomes as non-irradiated allografts due to preservation of the grafts' biomechanical properties. However, infection risk and/or re-injury, surgery waiting time and quality of life must all be considered when selecting a graft.

Aims and objectives

This project aims to evaluate the clinical efficacy of low-dose irradiated allografts for ACL reconstruction in vivo. Low-dose irradiated allograft outcomes will be compared to those of the current gold standard–autografts.

METHODS

Search strategy

A comprehensive search of EMBASE, PUBMED and SCOPUS was performed using the terms 'allograft AND (ACL repair OR ACL reconstruction OR) AND (gamma radiation OR low dose radiation) AND autograft'. Due to the lack of MeSH terms surrounding low dose radiation or

gamma radiation only non-MeSH terms were used. Appendix 1 demonstrates the generation of search results through each search term in the included databases. Searches conducted from inception to January 2025. Appendix 1 demonstrates the generation of search results through each search term in the included databases.

Studies were included on the condition the full-text paper was available in the English language and data sets were available for review. Abstracts were then screened to ensure they were cohort or randomized studies on humans and were in-vivo. Abstracts were also reviewed to confirm comparison was between allograft and autograft controls. Backward snowballing from review papers was used to identify papers that were missed through the primary search. The eligible studies were then de-duplicated using reference software Endnote.

Study selection

Following the first-pass search, the papers deemed eligible then underwent a full-text review according to the inclusion and exclusion criteria (Table 3). In order to be included, the paper methodology had to be a cohort or randomized control trial comparing allografts to autografts. Outcome measures had to be quantitative and reproducible variables, hence any studies with patient reported outcomes only were excluded. The studies left were included in the report. In this review we followed PRISMA 2020 to ensure transparent reporting: we completed the 27-item checklist (covering rationale, search methods, eligibility criteria, selection, risk of bias, synthesis and certainty) and included the PRISMA 2020 flow diagram (Figure 2) to document records identified, screened, excluded and included.

Quality assessment

The critical appraisal skills programme (CASP) tool for assessing cohort and randomized studies was used to measure the quality of the included studies (Table 4). Variables from each study were compared for autografts vs. low-dose irradiated allografts including graft failure/ revision surgery rates, arthrometer score of knee joint laxity and pivot shift measurements. International Knee Documentation Committee Subjective Knee Form (IKDC) scores were also reviewed. Included studies were further reviewed by two independent reviewers and if considered appropriate were selected for in-depth analysis in the literature analysis section of this report.

Evaluation of findings

The findings from each study were presented in table 4 in order to compare variables including graft failure/revision rates, arthrometer scores of knee joint laxity and pivot shift measurements. The significances of the findings were summarised in the context of autografts vs. low-dose irradiated allografts. International Knee Documentation Committee Subjective Knee Form (IKDC) scores were also considered in included studies which also provided other objective outcomes. Five studies were selected for in-depth analysis in the literature analysis section of this report (Table 5).

Following a search of the three databases and accumulation of papers identified through systematic reviews, the inclusion and exclusion criteria were applied as summarised in Figure 2.

Table 4 presents papers included in this study following the literature search with the addition of Tejwani et al, which has been selected as a seminal paper in comparing the effect of gamma irradiation on allografts at different dosages over a follow-up period of 2-years.[30] No meta-analysis was performed due to heterogeneity in irradiation doses and follow-up of the included studies and instead, a qualitative synthesis was performed.

RESULTS

The results of the literature search, alongside a summary of each included study's findings is presented in table 4. The bias concerns for each paper have been identified and discussed.

Graft failure rate

Graft failure rates vary across studies due to differing definitions and low incidence in follow-up cohorts. While young, high-activity patients exhibit higher failure rates (~7%), general population risk remains low, limiting the utility of graft rupture as a sole outcome measure.[30,32] Mechanical assessments offer a more consistent comparison. Ghodadra et al used Lachman, pivot shift and KT-1000 arthrometry, finding no significant differences in knee laxity between autografts and low-dose irradiated allografts over a one-year follow-up.[33] This was the case when 2.5 Mrad or lower radiation was used, suggesting that the dose-dependent collagen damage is perhaps not relevant in doses under 2.5 Mrad.

However, grouping processed and unprocessed allografts may obscure subtle differences due to omitted variable bias. Objective measures like the KT-1000 reduce examiner variability and outperform clinical tests such as the Lachman (which loses post-reconstruction sensitivity) and the pivot shift (which has high specificity but moderate sensitivity). Despite mixed evidence, low-dose irradiated allografts appear biomechanically comparable to autografts, supporting their broader use across age groups.

Age as a factor

While small studies lack power to assess graft failure rates meaningfully, Maletis et al analysed 5,586 ACL reconstructions and found higher revision rates in allografts (3.6%) compared to autografts (1.9%), especially in patients under 22 years old.[44] In contrast, outcomes in patients over 22 showed no significant

difference between low-dose irradiated allografts and autografts, aligning with Hulet et al, who reported superior allograft performance in patients over 25 (Figure 3).[34]

Age bias complicates interpretation, only 18.4% of the allograft group were under 22, versus 49.9% in the autograft group, suggesting clinician selection influenced by known age-dependent outcomes. Despite its strengths, the Maletis study lacked control over variables such as surgical timing and rehab protocols. Additionally, cost and logistical challenges of allografts, may limit their feasibility, especially in resource-constrained settings.[35] Nevertheless, the data support cautious use of allografts in older adults while reaffirming autografts as the preferred option in younger, more active patients. Clinician selection bias may overestimate allograft risks in young patients; propensity matching in future studies could address this.

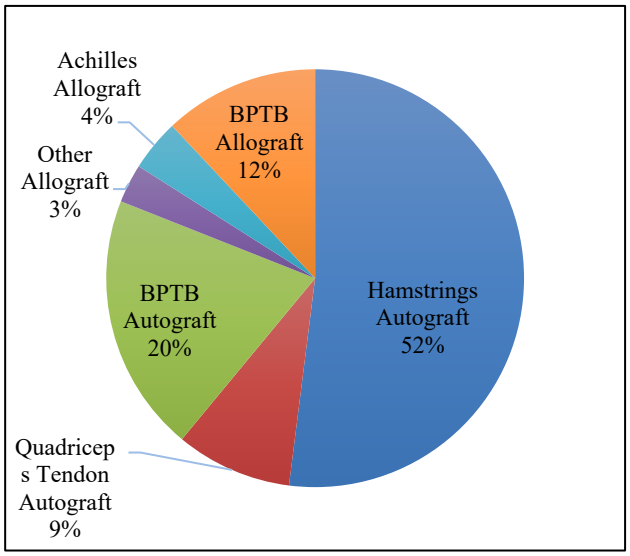


Figure 1: Proportion of different ACL graft types used currently in the UK.[46]

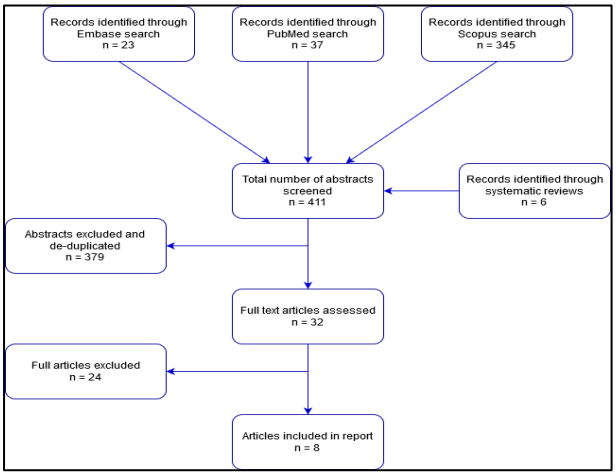
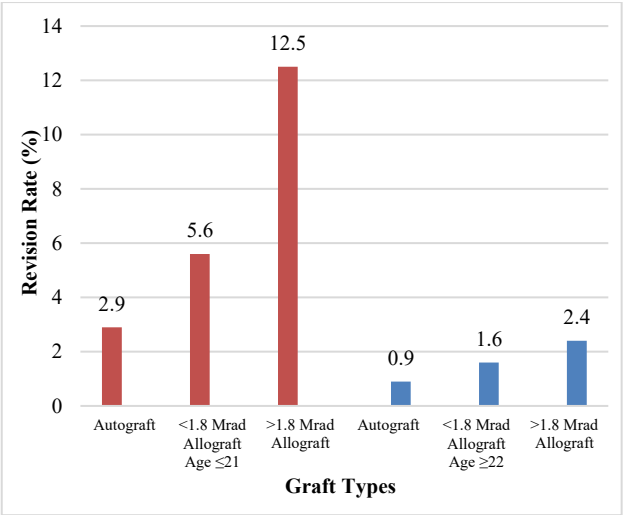


Figure 2: A flow-chart representing the study inclusion process based on preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines.[47]



*Statistically significant differences in values have been marked.

Figure 3: Reported revision rates (%) of different graft types by stratified by age.[44]

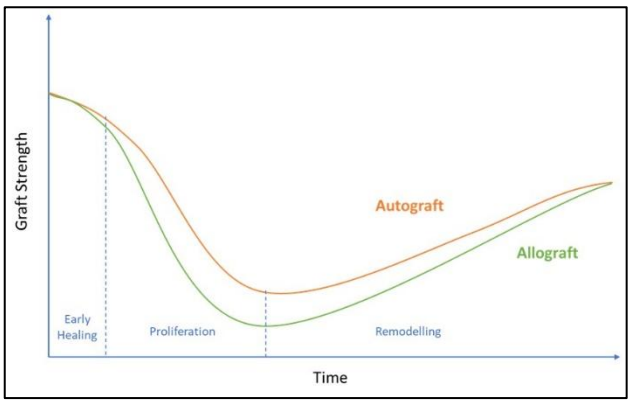


Figure 4: Different proposed timelines for graft healing in autografts and low-dose irradiated allografts.[31]

Are patient-reported outcome scores useful in measuring Anterior cruciate ligament graft success

In a five-year prospective RCT, Li et al found greater knee laxity in low-dose irradiated allografts (3.5 mm) compared to autografts (2.1 mm) via KT-1000 measurements, though Lachman and pivot shift tests showed no difference.[36] These findings were corroborated by Sun et al, Objective differences did not translate into statistically significant disparities in patient-reported outcome measures (PROMs).[24,37]

In Li et al no significant differences were found in Lysholm scores, Tegner activity levels or IKDC scores between graft types over a five-year follow-up.[36] This suggests that while biomechanical superiority exists, the functional experiences of patients may not differ appreciably, a finding with important implications for graft selection in routine clinical practice. If subjective function

is preserved, the relevance of small differences in laxity may be less impactful for certain patient populations.

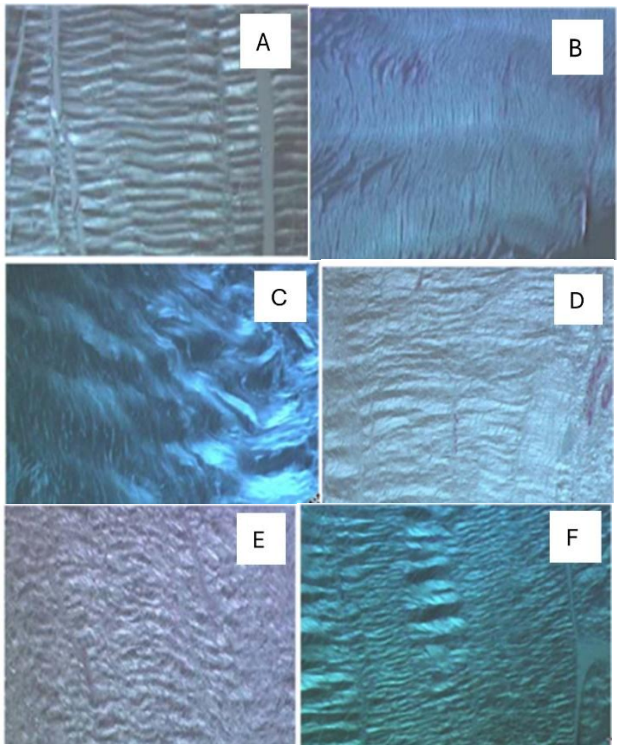


Figure 5: Light microscopy of ACL fibres and grafts during healing.

Graft choice after primary reconstruction failure

The MARS cohort, comprising 1205 patients and 87 surgeons, reported improvements in IKDC scores following revision ACL surgery in both autograft and low-dose irradiated allograft groups.[38] However, autograft recipients showed greater functional gains and there was a higher, though underpowered, re-rupture risk in allograft patients. No differences were noted between BPTB and soft tissue grafts within each graft type. Selection bias likely influenced results, as patients with prior autograft failure were more often assigned to the allograft group, particularly athletes who inherently face higher re-rupture risk.[39] The 2016 MARS analysis further noted surgeon preference as the strongest predictor of revision outcomes, though patient perceptions and prior graft dissatisfaction often influenced graft choice. Despite limitations such as non-randomization and short follow-up, findings suggest autografts may offer superior outcomes in revision ACL surgery, especially in younger, high-demand individuals.

Does the post-operative recovery time differ between allografts and autografts

Rihn et al conducted a four-year retrospective study comparing ACL reconstructions using autografts and low-dose irradiated allografts.[40] While knee laxity and IKDC scores were statistically similar between groups, autograft patients returned to weight-bearing one week earlier and resumed running one month sooner than those with allografts. This supports a consistent pattern across the literature autografts facilitate faster return to physical activity, a factor not fully captured by traditional outcome scores.[41] Biological differences in graft remodeling help explain this disparity. Autografts undergo remodeling more quickly (6-12 months), while allografts show delayed tissue integration (11-18 months).[42]

Although allografts may regain strength over a longer period, their slower adaptation limits early functional gains (Figure 4).[31] These findings suggest that short- to mid-term recovery is generally superior with autografts, even if long-term mechanical properties converge. However, disparity in rehabilitation protocols must be considered between the studies. While autografts enable faster early return a meta-analysis suggests higher long-term pre-injury activity restoration with allografts, possibly due to reduced donor morbidity.[40,43]

Table 1: Comparing ligament and tendon composition, adapted from Amis and Marieswaran et al.[7,8]

Component	Ligament (%)	Tendon (%)
Cellular material	20% (fibroblasts)	20 (tenocytes–fibroblast-like cells)
Collagen	70%	80
Type I collagen	90%	99
Type III collagen	10%	1
Elastin	Abundant	Scarce
Proteoglycans and GAGs	5%	<2

Table 2: Summary of ACL allograft revision rates for each dosage group reported in Tejwani et al.[30]

Irradiation dosage (Mrad)	Number of cases	Revision rate (%)
None	1185	2.28
<1.2	726	2.89
1.2-1.8	2911	2.23
>1.8	1146	3.75*

*Statistical significance when compared to the non-irradiated control group.

Table 3: A summary of the inclusion and exclusion criteria, including their justification, for identifying suitable papers in this report.

Exclusion criteria	Inclusion criteria	Justification of criteria
No controls	Autografts of the same graft type as control	This project aims to evaluate the efficacy of allografts that have been prepared using low dose gamma irradiation. Thus, only papers which include comparisons against the current gold standard for ACL repairs, autografts, were considered for this project.
No full-text paper available	Full-text paper available in English	For the purposes of evaluation of the findings of each included study, studies without the full-text available and those without their data published were also excluded.
No data available	Data sets available for review	
Case-studies and letters to editors	Cohort or randomised studies	
Animal studies	Human studies only	Furthermore, only human studies performed in vivo were considered in order for the findings of this project to have inferences for clinical practice.
In vitro studies	In vivo studies	
Outcomes measured with only patient reported data	Outcomes measured with quantitative and reproducible variables	Furthermore, due to lack of reliability of self-reported patient data especially in studies without randomised blinding, this project excluded any studies without objective and quantitative data as their measurable outcome.

Table 4: Characteristics of the 8 included papers from the literature search and backward snowballing, including study design, number of patients, outcomes measured and definitions for low-dose irradiated allografts. The key findings of each paper are summarised along with their significance in this report.

Reference	Study type (follow-up time)	No. of patients	Irradiation dosage & graft types	Outcome assessed	Key findings	Significance of findings	Bias concerns
Maletis et al[44]	Retro-spective cohort (2 years)	5586	Unprocessed, <1.8-Mrad and ≥1.8-Mrad BPTB	Aseptic revision	There were 37 (3.6%) revisions in BPTB allograft cases and 85 (1.9%) in BPTB autograft cases. The results varied significantly for age categories >22 and </=21. In over 22-year olds there was no difference in revision rates for autografts and allografts which received <1.8 Mrad. In the 21-year-old or younger patients, there was a stark difference in revision rates from 2.9% to 10.1% in autografts and allografts with low dose gamma radiation respectively.	This study supports the idea that autografts are mechanically superior *in vivo* to allografts. However, it raises suspicion over the effects of age on the healing of allografts. This being a retrospective study, times between injury and surgery were not standardised and thus a prospective study of similar size would be beneficial to the literature.	High risk of bias from age differences between each group's population. High risk of bias from disproportionate representation of allograft and autograft groups.
MARS cohort[38]	Prospective cohort (2 years)	1205	Unprocessed, <1.8Mrad Various Grafts	Re-rupture rates	This study analysed re-rupture rates in repeat ACL repairs. It was found that patients with an	This study suggests autograft use in repeat ACL reconstructions shows lower	Despite being a prospective study, there is no

Continued.

Reference	Study type (follow-up time)	No. of patients	Irradiation dosage & graft types	Outcome assessed	Key findings	Significance of findings	Bias concerns
				IKDC scores	autograft revision were found to be 2.78 times less likely of sustaining a subsequent graft rupture compared with subjects who received an allograft. However, patient reported outcomes such as activity or pain were inconsistent with contrasting results using one scoring tool versus another.	risk of graft rupture. This study is unique in its investigation of repeat reconstructions. The data on individual graft types is not given however and low failure rates meant the power to detect a difference was low. As such, failure rates reported are unreliable.	randomisation. This may introduce some bias as the previous reconstruction's graft type may have influenced graft choice in this study.
Li et al[36]*	Prospective Randomised (5 years)	102	2.5 Mrad Various Grafts	Knee joint laxity Pivot shift IKDC scores	No significant difference was found in Lachman test and pivot shift tests between allograft and autograft groups. The same was not the case with arthrometer readings and autograft patients showed more stable knee joints. Patient reported scores were not statistically different. Graft failure rates were not reported due to the small N number of the study.	Despite the arthrometer reading suggesting autografts were superior, this did not translate to functional differences in the context of patient experience. This suggests autograft and allograft repairs functioned equally in the context of patient experience. A larger N number is needed with a similar follow-up time in order to comment on failure rates.	Moderate risk of bias due to this being a single surgeon study.
Ghodadra et al[33]*	Retrospective Cohort (1 year)	238	Unprocessed, 1-1.3Mrad PT	Re-rupture rates Lachman's test Pivot shift Arthrometer measure	Laxity measured by arthrometer did not increase after the 6-week initial testing for either allograft and autograft group. There were no significant differences found between each of the groups in arthrometer, pivot shift and Lachman's test measurements. No differences between the unprocessed and low dose gamma irradiated grafts were found.	Found no differences between low dose irradiated allografts and autografts across 3 different mechanical testing modalities. However, they first compared the unprocessed allograft to the low dose allograft groups and found no significant difference, before then comparing a combined allograft group to an autograft group. This can	Moderate risk of bias due to single surgeon and single examiner being used for reconstruction and further testing.

Continued.

Reference	Study type (follow-up time)	No. of patients	Irradiation dosage & graft types	Outcome assessed	Key findings	Significance of findings	Bias concerns
						potentially skew the statistical tests.	
Tejwani et al[30]	Retrospective Cohort (2 years)	5968	Unprocessed, <1.2, 1.2-1.8, >1.8 Mrad Various Grafts	Revision rates	This study investigated the effects of different dosages of allografts with each other, as well as the effects of other processing methods for allografts including chemical preparation. It found that within the first year of ACL repair, non-irradiated, low dose irradiated and high dose irradiated allografts had no significant differences in graft failure rates. However, after a year, low dose irradiated showed a lower risk for failure than the higher dose.	This study comments solely on non-irradiated vs. low dose vs. high dose irradiated allografts. Despite the longer follow-up time and large N number, there was no randomisation of groups and no standardisation of graft types. As only revision rates were considered, graft failures which did not lead to revision surgery were not considered in the results.	High risk of bias due to the non-randomised and non-standardised variables in each ACL repair recorded.
Rihn et al[40]*	Retrospective Cohort (4 years)	102	2.5 Mrad BPTB	Activity level Knee joint laxity IKDC scores Radiograph findings	This study found there to be no statistical significance between knee joint laxity of allograft and autograft treated patients when adjusted for age. There was statistically significant differences in the raw data before age adjusting. There were no significant differences for patient reported IKDC scores and return to activity scores between the two groups.	This study demonstrates the ability of low dose sterilised allografts to produce the same clinical outcomes as autografts in ACL repairs. The patient reported and objectively measured factors were statistically indifferent. Although it must be considered that this is with age adjusted results and raw data showed statistical differences between the groups.	Moderate risk of bias from age differences between each group's population and time from injury to reconstruction. Due to retrospective data, there are no comparisons to laxity before graft repair.
Sun et al[24]	Prospective Randomised (2.5 years)	99	2.5 Mrad BPTB	Re-rupture rates Arthrometer Pivot shift IKDC scores	This study found there to be no functional differences in the knees of allograft vs. autograft treated patients including range of motion, vertical jump and IKDC scores. However, they found statistical differences in	This study suggested that short term clinical outcomes are affected in low dose irradiated allografts compared to autografts. The higher rates of failure for the allograft group found in this	Moderate risk of bias due to this being a single surgeon study. These studies were carried out by the same group.

Continued.

Reference	Study type (follow-up time)	No. of patients	Irradiation dosage & graft types	Outcome assessed	Key findings	Significance of findings	Bias concerns
					knee laxity for side-to-side differences in anterior tibial displacement, pivot shift and Lachman test.	study supported the choice of autografts in ACL repairs.	
Sun et al[37]	Prospective Randomised (2.5 years)	67	2.5 Mrad Hamstring Tendon	Arthrometer Pivot shift IKDC scores	This study found the rate of laxity to be higher in allograft treated knees than in the autograft group. There was significantly higher rotational instability in the allograft group than in the autograft. However, there were no functional differences reported by patients in IKDC scores and activity testing.	This study suggested that short term clinical outcomes are affected in low dose irradiated allografts compared to autografts.	

*Papers will be discussed in further detail. All irradiation dosages have been converted to Mrad units for ease of comparison. One rad is defined as 0.01 Joules of energy absorbed by 1kg of tissue, 1 Mrad is equivalent to 1 million of the rad unit. Bias concerns for each paper have been categorised as low (green), moderate (amber) and high (red).

Table 5: List of studies selected for further analysis and justifications for their selection.

Study	Justification for in-depth analysis
Maletis et al[44]	This study was chosen due to its large sample size allowing for reporting of graft failure rates with adequate statistical power. Furthermore, data provided in this study was stratified by age and allowed discussion of age-related outcomes of ACL autografts compared to low-dose irradiated allografts.
MARS cohort[38]	This study was the only one included in this report which considered revision surgery following an initial graft failure. It included prospective data shared by 52 clinical centres which makes the findings of this study applicable for a wider population across ages and levels of activity.
Li et al[36]	This study was selected due to its long follow-up time and variety of measured outcomes. These included both objective mechanical testing and patient reported scores to evaluate the success of autografts compared to low-dose irradiated allografts.
Ghodadra et al[33]	This study was selected due to its incorporation of both graft failure and mechanical testing of a graft post-operatively as outcome measures. This allowed for an evaluation of graft rupture as a suitable measure of graft success.
Rihn et al[40]	This study was selected as it was the only study included in this report to look at rates of return to physical activity as an outcome measure. Its long follow-up period and use of both patient-reported factors and mechanical testing add context to its findings regarding return to activity rates in autografts compared to low-dose irradiated allografts.

Table 6: Summary of laxity measurements defined as side-to-side difference of anterior tibial displacement of the graft knee compared to the contralateral knee across 3 studies which used KT-1000 and KT-2000 arthrometry.

Study	Laxity measured (mm)	
	Autograft	Low-dose irradiated allograft
Li et al[36]*	2.1±1.6	3.5±1.2
Sun et al[24]*	2.4±0.6	5.5±3.6
Sun et al[37]*	2.3±1.1	3.6±2.8
Rihn et al[40]*	1.3±2.3	2.2±2.0

*All studies reported statistically significant laxity measurements between the autograft and low-dose irradiated allograft groups.

DISCUSSION

Principal findings and interpretation

Across eight studies (>10,000 patients), autografts showed lower failure/revision risk in younger, high-demand patients, whereas outcomes were broadly comparable in older cohorts. Specifically, revision risk was higher with allografts in patients ≤21 years (10.1% vs 2.9%), but not different in those >22 when low-dose irradiation was used, indicating that age/activity level modifies any irradiation-related decrement in performance.[30,44] Objective laxity was generally greater after low-dose γ-irradiated allografts-typically ≤2.5 Mrad in the RCTs-by KT-1000/2000 yet these differences rarely translated into worse PROMs (IKDC/Lysholm/Tegner) over 2–5 years.[24,36,37,40] Clinically, autografts supported earlier functional milestones (e.g., weight-bearing and running) consistent with faster ligamentization.[40,42]

Dose effects and graft processing

The largest cohort to stratify dose reported no early (<1 year) difference among non-irradiated, low-dose (<1.8 Mrad) and higher-dose groups, but beyond one year failure risk rose with >1.8 Mrad, supporting a dose–response detriment to collagen integrity at moderate doses (30). These clinical observations align with bench data showing irradiation-induced collagen chain scission and reduced tensile properties in a dose-dependent fashion.[22,23,28]

Comparison with previous syntheses

Our pattern greater early laxity yet similar short- to mid-term PROMs for irradiated allografts—accords with prior meta-analyses finding higher failure with allografts overall but small between-group differences in functional scores.[21,25,29] The age-contingent effect we observed echoes registry-based and multi-centre series in which autografts outperform allografts in young, cutting/pivoting athletes, while differences attenuate with age and lower activity levels.[38,44]

Revision settings

In revision ACLR, the MARS cohort found improved IKDC with both graft types but higher (under-powered) re-rupture risk after allograft and greater functional gains after autograft, suggesting autograft preference in young revisions where tissue quality and loading demands are greatest.[38]

Clinical implications

For patients ≤21 years or returning to pivoting sport, autografts remain preferable given lower failure risk, earlier functional recovery and superior early stability.[38,40,42,44] Low-dose (≤~1.8–2.5 Mrad) irradiated allografts are reasonable in older or less active individuals where avoiding donor-site morbidity and operative time is prioritized, with the caveat that early laxity may be higher and ligamentization slower.[24,36,37,40,42] Doses >1.8 Mrad should be avoided when possible due to higher late failure risk.[30]

CONCLUSION

This review examined the comparative effectiveness of autografts and low-dose irradiated allografts in ACL repair, particularly focusing on mechanical integrity, patient-reported outcomes and long-term graft viability.

Autografts consistently show superior early biomechanical outcomes, particularly in younger patients. Several studies, including Li et al, report better knee laxity with autografts despite no difference in patient-reported outcomes such as IKDC scores.[36] This was the case when 2.5 Mrad or lower radiation was used, suggesting that the dose-dependent collagen damage is perhaps not relevant in doses under 2.5 Mrad. While subjective measures are important for assessing quality of life and functional return to sport, they may fail to capture clinically significant mechanical deficits. Notably, knee laxity is a better predictor of re-injury risk and potential osteoarthritis development, favoring autograft use for reducing long-term joint degeneration.

Revision rates further reinforce this preference. Maletis et al showed autografts to have significantly lower failure rates than allografts in patients under 22, with no difference in older cohorts.[44] This may be linked to the slower remodeling capacity of allografts and potential complications with bone incorporation, particularly when using donor bone from older individuals. Advances in soft tissue graft fixation now allow for effective use of hamstring or quadriceps autografts in skeletally immature patients, supporting a broader autograft strategy.

Although some evidence suggests that allografts can ultimately regain equivalent or greater strength through prolonged remodeling, short follow-up durations common in the literature may underestimate their long-term potential.[31] Still, delayed return to sport and higher early laxity rates raise concerns about allograft suitability in younger or high-demand individuals. However, a meta-analysis of 17 studies comparing return to pre-injury activity levels between BPTB allograft and autograft recipients found a significantly higher proportion of successful returns in the allograft group (68.3%) compared to the autograft group (57.1%), with the odds ratio favoring allografts.[43]

Interpretation of the literature is complicated by methodological inconsistencies, retrospective designs, non-randomized graft selection, lack of standardised rehabilitation protocols and variation in surgical techniques (e.g., single vs double-bundle reconstructions). These factors contribute to outcome heterogeneity and limit definitive conclusions. Moreover, the inconsistency in defining graft failure, particularly in athletic populations where contralateral injuries are common, adds further complexity.

In summary, autografts remain the graft of choice for younger, active patients due to their superior mechanical stability, faster incorporation and lower failure rates. Low-dose irradiated allografts may be suitable alternatives in older, less active individuals, but their long-term efficacy remains uncertain without higher-quality, standardised studies. Future research should priorities long-term, prospective trials that integrate mechanical outcomes with patient-reported data and clearly defined revision criteria. The cost and logistical challenges of low-dose irradiated allografts must be considered. Given the increased cost in sourcing an allograft and the irradiation sterilisation process, autografts may still be the preferred option by health services. However, in patients for whom avoiding donor-site morbidity is paramount, patients who are at risk of longer operative times and patients in whom immunologic reactions are unlikely, an alternative to autografts is viable.[45]

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