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MRI evaluation of the anterior cruciate ligament graft post-arthroscopic reconstruction – A non-invasive comprehensive assessment

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Background: Anterior Cruciate Ligament (ACL) reconstruction is a common orthopaedic procedure, the success of which is ultimately affected by the graft healing process. Quantification of graft healing can be performed non-invasively, using signal-intensity (SI) or signal noise quotient (SNQ) on MRI, however, the variable factors affecting graft healing are still being studied.

Objectives: To non-invasively evaluate the normal morphology of the ACL graft on MRI and assess factors affecting graft healing post-arthroscopic ACL reconstruction.

Method: A single-centre cross-sectional study was performed using MRI scans for assessment of the ACL graft at 6 months to 2 years post-surgery. Signal noise quotient was correlated with tibial tunnel diameter, femoral tunnel diameter, tibial tunnel location (antero-posterior and medio-lateral), femoral tunnel location (high-low and deep-shallow), graft bending angle (GBA) and notch volume.

Results: Twenty-four of 42 patients had normal grafts (mean ± standard deviation post-operative time: 10.15 ± 4.38 months). The SNQ levels were highest at the proximal part of the graft. Graft SNQ correlated positively with tibial ($p = 0.020$) and femoral ($p \leq 0.001$) tunnel diameters, tibial tunnel location in the medio-lateral direction ($P \leq 0.001$), femoral tunnel location in the high-low direction ($p \leq 0.001$) and patients having complications. Graft SNQ correlated negatively with tibial tunnel location in the antero-posterior (AP) direction ($p \leq 0.001$). Univariate analysis revealed a significant correlation between SNQ and tibial and femoral tunnel diameter, tibial tunnel location in both AP and medio-lateral directions, femoral tunnel location in high-low direction and patients having complications. Multivariate analysis showed the tibial tunnel location (medio-lateral) and the femoral tunnel location (high-low) as the significant independent factors.

Conclusion: Intraoperative factors, predominantly the positions of the tibial and femoral tunnels, are the major factors affecting graft healing.

Contribution: This study provides greater awareness regarding the factors affecting graft healing, helps establish MRI as an effective non-invasive post-operative imaging modality, and helps surgeons in providing a better individualised approach to surgery.

Keywords: MRI; ACL graft; signal noise quotient; tibial tunnel; femoral tunnel; signal intensity.

Introduction

With an increase in the number of anterior cruciate ligament (ACL) reconstructions, it has become important to assess the graft status postoperatively in the form of graft healing and to look for re-injury.[1] Even with the advances in surgical and rehabilitation techniques, graft injury is a concerning consequence.[2]

Previous studies have reported that quantification of graft healing can be performed non-invasively, using signal intensity (SI) or signal noise quotient (SNQ) on MRI.[1,2,3] Graft healing

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occurs at two sites, that is, intra-articular maturation and intra-tunnel integration.[1] Although graft healing is mainly a biological process, multiple other anatomical (age, sex, body weight, tibial slope, intercondylar notch width), operative (type of graft, graft bending angle, femoral and tibial tunnel dimensions and location, rich fibrin application, remnant preservation, partial meniscectomy), and post-operative factors (time, activity level) have also been identified to affect the process.[1,2,3]

One of the main reasons for unsuccessful ACL reconstruction is graft failure. A large majority of cases (22% – 79%) of graft failure are attributed to technical errors, of which the commonest is improper tunnel placement.[4] It was reported by Marchant et al. that about 88% of ACL reconstructions fail because of non-anatomical positioning of the graft.[5] It has been noted that restoring the native anatomical characteristics of ACL improves the kinematics of the knee, increases anterior and posterior, as well as rotational stability, and decreases the pivot shift postoperatively.[6] There are only a few studies on this multifactorial approach to graft healing in the literature.[1,2,3,7]

The current study aims to identify the factors that affect graft healing with their combined effect, based on signal intensity on 3T MRI, which will help surgeons provide a better individualised intra-operative approach to surgery in relation to patient demographics and anatomy, and can promote maximum and early graft healing.

Research methods and design

A single-centre, cross-sectional, prospective study was performed between January 2023 and May 2024 to assess ACL grafts post operatively at follow-up after 6 months to 2 years. According to the study conducted by Ma et al. (2015),[8] with an alpha error of 0.05 and beta error of 0.2, the authors used the formula of means based on the hamstring graft; utilising a group mean of 2.4 and standard deviation of 0.6, the minimum required sample size was calculated to be 38. A slightly higher number of 42 patients were included in this study using consecutive sampling to accommodate for any unknown complications. Of these, 3 patients with complete graft rupture were excluded from the analysis.

The inclusion criteria were patients following primary single bundle ACL reconstruction using autologous grafts who had undergone an MRI scan of the knee after at least 6 months of follow-up. Patients with MRI-incompatible implants, claustrophobic patients, and metabolic or neoplastic bone diseases were excluded. The following factors were evaluated – age, sex, post-operative time, tibial tunnel diameter, femoral tunnel diameter, tibial tunnel location AP (antero-posterior), tibial tunnel location medio-lateral (ML), femoral tunnel diameter HL (high-low), femoral tunnel diameter DS (deep-shallow), graft bending angle (GBA) and notch volume. All patients underwent single-bundle ACL reconstruction with ipsilateral autologous hamstring tendon (semi-tendinosus and/or gracilis) or peroneus longus grafts.

Imaging technique and analysis

MRI examinations were performed in the supine position, feet first, with full limb extension, on a 3T MR scanner (Siemens Healthineers® Magnetom Skyra) with a knee coil (15 elements, 15 channels). The sequences and their parameters, which were included in the MRI protocol, are summarised in Table 1.

All MRI images were evaluated using a Syngo.via Advanced Workstation 11.8® Siemens Healthineer. Signal noise quotient (SNQ) and other graft-related parameters, like GBA, were obtained on all the scans, except for the patients with complete graft disruption. Other tunnel-related parameters, including, femoral tunnel diameter and location, tibial tunnel diameter and location, and volume of notch were derived for all patients.

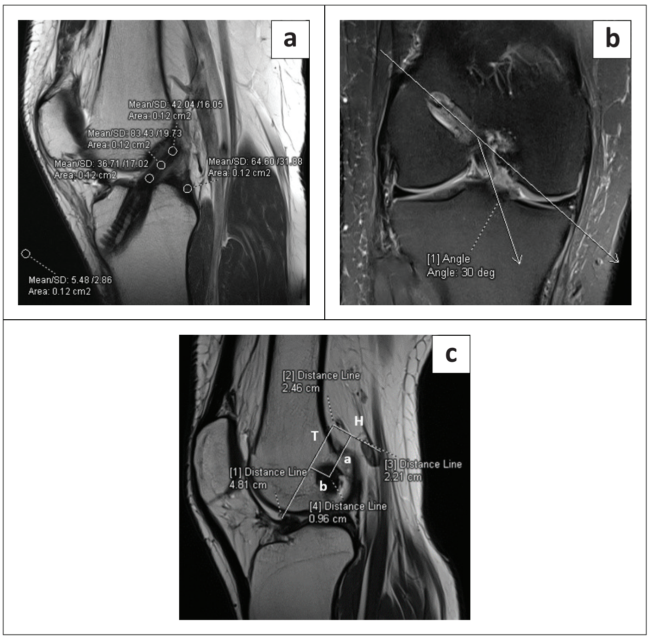
Signal noise quotient was determined according to Oshima et al.[3] on the sagittal T2W (T2-weighted) image, using the following formula : $SNQ_{acl} = (SI_{acl} - SI_{pcl})/SI_{background}$. SI was calculated by drawing a circular region of interest (ROI) of areas between 10 mm^2 – 15 mm^2, at the proximal, mid and distal parts of the intra-articular graft (Figure 1). The mean of the three regions was used as an SNQ of the graft.[3] Graft bending angle was calculated on the coronal proton density fat-saturated (PD FS) sequence by drawing the angle between the femoral tunnel and the intra-articular portion of the graft (Figure 1).[3]

The modified quadrant method was used to measure the femoral tunnel location, in which the maximum length and height of the femoral condyle were measured in millimetres from the proximal condylar surface parallel to the Blumensaat line (T) and from the notch roof perpendicular to the Blumensaat line (H), respectively, on a sagittal T2W image. The measurement between the centre of the femoral tunnel and the proximal ends of line T (a) and line H (b) were

TABLE 1: Parameters of the sequences acquired.

Sequence	TR	TE	Slice thickness	FOV	phase	NEX	Bandwidth	matrix
T1 SE COR	410	19	3 mm	13 × 10 cm	448	1	243Hz/px	269 × 448
T2 SE SAG	4000	70	3 mm	14 × 10 cm	384	1	221Hz/px	307 × 384
PD-FS SE AX	3700	44	3 mm	13 × 10 cm	384	2	255Hz/px	269 × 384
PD-FS SE SAG	3200	37	3 mm	13 × 10 cm	320	1	240Hz/px	256 × 320
PD-FS SE COR	3000	37	3 mm	13 × 10 cm	320	1	240Hz/px	256 × 320
T2 MED GE SAG	609	14	3 mm	13 × 10 cm	320	1	252Hz/px	256 × 320
3D-PD without FS	1400	30	0.8 mm	10 × 16	-	-	389Hz/px	192 × 192

TR, repetition time; TE, time to echo; FOV, field of view, NEX, number of excitation; COR,coronal; SAG, sagittal; AX, axial; PD, proton density; SE, spin echo; GE, gradient echo; FS, fat saturated.



PDFS, proton density fat-saturated; SD, standard deviation; deg, degrees.

FIGURE 1: Method of measuring signal noise quotient, graft bending angle and femoral tunnel location in high-low direction and deep-shallow direction: (a) Sag T2W image showing the method to measure the graft bending angle with region of interests drawn on the anterior cruciate ligament graft at three points, on the posterior cruciate ligament and the background. (b) Cor PDFS image showing the angle between the lines connecting the intra-articular part of the graft and the femoral tunnel. (c) T2 Sag image showing T and H lines indicating the maximum femoral condyle length from the proximal condylar surface parallel to the Blumensaat line and the femoral condyle height measured in the direction perpendicular to the Blumensaat line, respectively. The deep-shallow location is measured as the ratio of line joining the centre of the femoral tunnel up to line H (a) and line T. The high-low location is measured as the ratio of the line from the centre of the femoral tunnel up to line T (a) and line H.

acquired (Figure 1). The ratios of a:T (deep-shallow direction) and b:H (high-low direction) were then calculated.[3]

Tibial tunnel positioning was assessed using medial or lateral position ratio (length from medial edge of the tibial plateau to the centre of the tibial tunnel, divided by the total width of the tibial plateau) and anterior-posterior position ratio (length from anterior edge of tibial plateau to centre of tibial tunnel divided by total antero-posterior length which were measured on the 3D proton density (3D PD) sequence[9] (Figure 2). Femoral notch volume was calculated by tracing the femoral notch, using volume of interest (VOI), on every slice of the axial 3D PD sequence (Figure 3).[3] The femoral and tibial tunnels were measured in the axis of the tunnels on the 3D PD sequence at their maximum diameter in the coronal and sagittal oblique planes, respectively (Figure 4).

Statistical analysis

Data were analysed using STATA version 10.1 (2011) from StataCorp. Texas (US). Descriptive statistics of quantitative variables were described using means or standard deviations and medians or interquartile ranges (IQR) for continuous variables. Qualitative or categorical variables were summarised using frequency and percentages. Inferential statistics procedures were applied to test hypotheses about associations and differences in MRI parameters. An independent sample t-test was used to make comparisons between two groups of

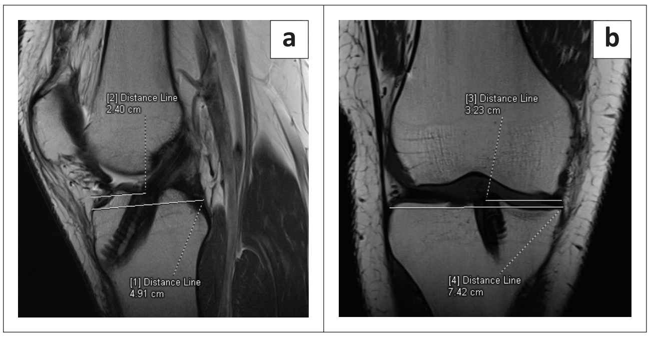
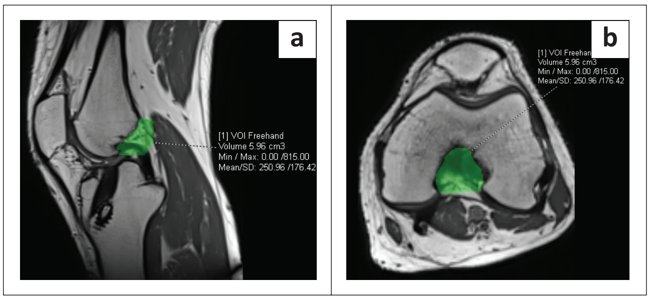


FIGURE 2: Method for measuring the tibial tunnel location in (a) antero-posterior (AP) direction and (b) medio-lateral (ML) direction: T1 Sag and Cor images showing the method for measurement of the tibial tunnel location by measuring the tibial plateau in the mediolateral and anteroposterior direction and the distance of the centre of the tibial tunnel from the anterior and medial edge respectively, and then calculating the ratio individually for both planes.



PDFS, proton density fat-saturated VOI, volume of interest; Min, minimum; Max, maximum; SD, standard deviation.

FIGURE 3: (a, b) Method for measuring the femoral notch volume: 3D-PDFS Sag and Axial section showing VOI in green colour denoting the volume of the intercondylar notch.

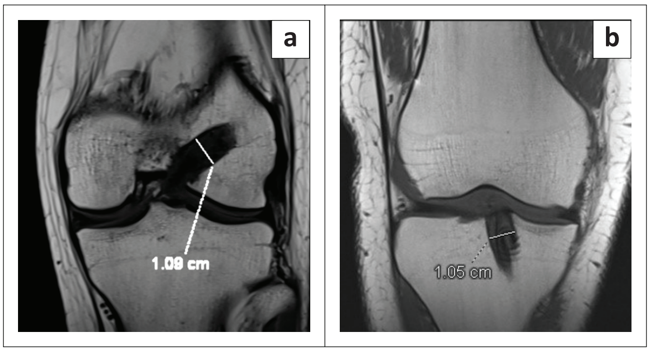


FIGURE 4: Method for measuring (a) femoral tunnel and (b) tibial tunnel size: The maximum diameter of the tunnels was measured in T1 Cor sections as shown in the picture.

categorical variables (complications); if the other variable was continuous, data were distributed normally in both groups. If continuous data were non-normally distributed between two groups of categorical variables (gender, type of graft), the Wilcoxon Mann-Whitney U-Test was used. For making a comparison between multiple subgroups of a categorical variable (age) with non-normally distributed continuous data, the Kruskal-Wallis Test was used. Fisher's Exact test was used for making group comparisons if both variables were of categorical data (e.g., between the type of graft and gender) and in which the expected frequency in the contingency tables was found to be < 5% for > 20% of the cells. Correlation between two continuous variables was explored using Pearson's correlation, if both the variables showed normal distribution, like SNQ (graft), SNQ (proximal), SNQ (mid-substance), femoral tunnel location (high-low), notch volume, etc. Spearman's correlation was used for correlation between two continuous variables if any one of them was not normally distributed, for example, age (years), time (months), tibial tunnel location (ML), etc. Univariate regression analyses were performed to recognise the factors that affect the SNQ value of the graft. Multivariate analysis was carried out using binary logistic regression analysis to adjust for confounding factors. *P* value < 0.05 was considered statistically significant for all comparisons and associations.

Ethical considerations

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Ethical clearance to conduct this study was obtained from All India Institute of Medical Sciences, Nagpur, and the Institutional Ethics Committee of All India Institute of Medical Sciences on 25 January 2023 (reference number: IEC/Pharmac/2023/536), and written informed consent was obtained from all included participants.

Results

A total of 42 patients were included in this study, of which 24 patients had no significant abnormal findings on MRI. 14 patients had complications other than graft disruption. Complete graft disruption was found in three, while partial graft disruption was noted in one. The patients with complete graft disruption were excluded from the assessment of the association between SNQ and other factors. However, they were included for other analyses. A total of 9 patients had other minor complications like graft impingement, graft laxity, joint effusion, tunnel cysts, tunnel enlargement, abnormally positioned tunnels and hardware failure.

The mean age of the patients was 29.33 ± 9.27 years, and the mean time between surgery and post-operative MRI was 10.15 ± 4.38 months. Hamstring grafts were used in 76.9% of patients, while peroneus longus grafts were utilised in 23.1%. The demographic and operative characteristics are summarised in Table 2.

The mean SNQ values of the graft were as follows: entire graft 7.59 ± 3.86; proximal graft 9.33 ± 4.85, mid-substance 9.11 ± 5.61; and distal graft 4.57 ± 3.66. The mean SNQ was least at the distal aspect of the graft, while the maximum SNQ was found to be at the proximal part of the graft. The rest of the MRI measurements are summarised in Table 3. The mean SNQ (graft) in patients with complications was 9.29 ± 3.99, and in those without complications was 6.13 ± 3.14. The mean SNQ was significantly higher ($p = 0.011$) in patients with complications (Table 4).

Graft SNQ correlated positively with tibial (r = 0.37, $p = 0.020$) and femoral (rho = 0.65, $p \leq 0.001$) tunnel diameter, tibial tunnel location in the ML direction (rho = 0.66, $p \leq 0.001$), femoral tunnel location in the high-low direction (r = 0.7, $p \leq 0.001$) and with patients having complications (Table 4). A negative correlation was found between graft SNQ and tibial tunnel location in the AP direction (rho = −0.72, $p \leq 0.001$). No correlation was found between graft SNQ and age, gender, timing of post-operative MRI, type of graft, GBA and notch volume.

Regression analysis of individual factors with graft SNQ indicated a significant correlation with tibial and femoral tunnel diameter, tibial tunnel location in both the AP and ML directions, femoral tunnel location in the HL direction and with patients having complications (Table 5). Multivariate regression analysis revealed tibial tunnel location (ML) and femoral tunnel location (HL) as the significant independent factors affecting the graft SNQ (Table 5).

TABLE 2: Summary of demographic, postoperative duration, and type of graft details of the subjects.

Basic details	Mean ± s.d.	Median	IQR	Min – max range	*n*	%
Age (years)	29.33 ± 9.27	27.00	22.50–34.00	17.00–55.00	-	-
< 20	-	-	-	-	3	7.7
20–29	-	-	-	-	21	53.8
30–39	-	-	-	-	10	25.6
40–49	-	-	-	-	3	7.7
50–59	-	-	-	-	2	5.1
Gender						
Male	-	-	-	-	34	87.2
Female	-	-	-	-	5	12.8
Time (months)	10.15 ± 4.38	8.00	7.00-13.00	6.00–21.00	-	-
Type of graft						
Hamstring	-	-	-	-	30	76.9
Peroneus Longus	-	-	-	-	9	23.1

IQR, interquartile range; s.d., standard deviation; OR, odds ratio; Min, minimum; max, maximum.

TABLE 3: Summary of MRI measurements.

Parameters	Mean ± s.d.	Median	IQR	Min–Max
SI				
Proximal	90.42 ± 39.49	89.80	68.31–111.87	23.9–225.2
Mid	88.53 ± 41.71	79.15	57.44–120.93	26.5–179.1
Distal	55.86 ± 30.54	52.26	31.88–71.20	19.9–137.6
SNQ				
Graft	7.59 ± 3.86	6.60	4.53–10.44	1.1–14.9
Proximal	9.33 ± 4.85	8.83	6.03–12.53	1.0–19.0
Mid-substance	9.11 ± 5.61	8.61	4.23–13.93	1.5–23.0
Distal	4.57 ± 3.66	4.08	1.33–7.30	0.1–14.4
Tibial tunnel location				
Antero-posterior	0.44 ± 0.05	0.42	0.41–0.46	0.3–0.5
Medio-lateral	0.45 ± 0.03	0.46	0.44–0.47	0.3–0.5
Femoral tunnel location				
Deep shallow	0.35 ± 0.05	0.35	0.32–0.38	0.2–0.5
High–Low	0.39 ± 0.10	0.38	0.32–0.47	0.2–0.6
Femoral tunnel diameter (mm)	10.14 ± 1.16	10.20	9.12–10.65	8.6–13.6
Tibial tunnel diameter (mm)	11.01 ± 1.29	11.00	10.05–11.60	7.9–14.6
Graft bending angle (degrees)	33.87 ± 5.88	33.00	30.00–37.50	20.0–50.0
Notch volume	6.15 ± 1.53	5.97	4.93–7.19	3.7–10.9

SNQ, signal noise quotient; SI, signal-intensity; IQR, interquartile range.

Discussion

With an increase in the understanding of the anatomic, intraoperative and post-operative factors affecting graft healing, previous studies have emphasised the importance of the individualised approach with regard to ACL reconstruction.[3,10] This study found that SNQ was significantly associated with SI (proximal), SI (mid), SI (distal), SNQ (proximal), SNQ (mid-ubstance), SNQ (distal), femoral tunnel diameter (mm), tibial tunnel diameter (mm), tibial tunnel location (AP), tibial tunnel location (ML), femoral tunnel location (high – low) and complications. No significant association was found with age, gender, postoperative time (months), type of graft, GBA (degrees), and notch volume.

TABLE 4: Summary table for the association between signal noise quotient (graft) and parameters.

Parameters	SNQ (graft)		*p*
	Correlation coefficient (rho)	Mean ± s.d.	
Age (years)†	0.19	-	0.248
Age‡	-	-	0.176
< 20	-	9.36 ± 4.10	-
20–29	-	6.45 ± 3.23	-
30–39	-	9.66 ± 4.38	-
40–49	-	8.54 ± 3.37	-
50–59	-	5.14 ± 5.78	-
Gender§	-	-	0.172
Male	-	7.23 ± 3.64	-
Female	-	10.06 ± 4.83	-
Time (months)†	0.26	-	0.113
Type of graft§	-	-	0.868
Hamstring	-	7.59 ± 3.93	-
Peroneus Longus	-	7.61 ± 3.82	-
SI (proximal)¶	0.58	-	< 0.001*
SI (mid) ¶	0.75	-	< 0.001*
SI (distal)†	0.63	-	< 0.001*
SNQ (proximal) ¶	0.78	-	< 0.001*
SNQ (mid-substance)¶	0.88	-	< 0.001*
SNQ (distal)†	0.72	-	< 0.001*
Graft bending angle (degrees)¶	-0.04	-	0.808
Femoral tunnel diameter (mm)†	0.65	-	< 0.001*
Tibial tunnel diameter (mm) ¶	0.37	-	0.020*
Tibial tunnel location (antero-posterior)†	-0.72	-	< 0.001*
Tibial tunnel location (medio-lateral)†	0.66	-	< 0.001*
Femoral tunnel location (deep-shallow)¶	0.3	-	0.067
Femoral tunnel location (high–low)¶	0.7	-	< 0.001*
Notch volume¶	0.02	-	0.901
Complications††	-		0.011*
Yes	-	9.29 ± 3.99	-
No	-	6.13 ± 3.14	-

SNQ, signal noise quotient; SI, signal-intensity.

†, Spearman correlation; ‡, Kruskal Wallis test; §, Wilcoxon-Mann-Whitney U test; ¶, Pearson's correlation; ††, *t*-test.

*, Significant at $p < 0.05$.

Multiple previous animal and human studies, assessing the relationship between SNQ or SI and tissue quality, suggesting graft healing, have helped in establishing MRI as a non-invasive tool for graft assessment.[3,11,12,13] The studies were conducted to understand normal graft remodelling by monitoring SNQ on MRI scans, reflecting the ligamentisation of the graft. Graft healing comprises the following stages: avascular necrosis, neovascularisation, cellular repopulation and resynovialisation.[1] The maturation of the graft can be enhanced with remnant preservation,[14] a surgical method that was used in most of the patients in the present study.

In this study, the mean graft SNQ was 7.59 ± 3.86 (Range 1.1 – 14.9), which is slightly higher than in previous studies.[2,3] The higher value was likely to be attributed to an early mean post-operative time, which was 10.15 ± 4.38 months and confounding factors like activity level, graft volume and other anatomical factors. Values were highest in the proximal part (9.33 ± 4.85) and lowest in the distal aspect (4.57 ± 3.66), which is concordance with the pattern found by Ae et al.[2] This could be because of increased load and repetitive stress due to bending at the opening of the femoral tunnel.[15] There was no significant association between graft SNQ and post-operative time, which was similar to the results obtained by Oshima et al., who also had a similar mean post-operative MRI scan time.[3]

No significant difference was found in graft SNQ among males and females ($P = 0.172$), similar to studies performed by Ae et al. and Oshima et al.[2,3] This was contrary to the previous belief that gender affects graft healing owing to differing hormone levels among men and women.[16,17] There was also no correlation found with the age of the patients in the present study, which is concordant with the study performed by Li et al. and is possibly because of the fact that the majority of the participants were above 20 years of age.[1] Patients less than 20 years of age have shown to have more chances of rupture, because they usually return to aggressive activity earlier and hence also have been known to show a higher SNQ levels.[1]

TABLE 5: Multivariate regression analysis for factors affecting signal noise quotient values.

Parameter	SNQ (mean ± s.d.)	Coefficient (univariable)			Coefficient (multivariable)		
		β	CI	*p*	β	95% CI	*p*
Femoral tunnel diameter (mm)	7.6 ± 3.9	1.74	0.79 to 2.68	0.001	0.29	-0.45 to 1.02	0.428
Tibial tunnel diameter (mm)	7.6 ± 3.9	1.11	0.18 to 2.03	0.020	0.41	-0.30 to 1.12	0.252
Tibial tunnel location (antero-posterior)	7.6 ± 3.9	-57.87	-78.32 to -37.42	< 0.001	-18.86	-40.66 to 2.93	0.087
Tibial tunnel location (medio-lateral)	7.6 ± 3.9	80.77	48.69 to 112.85	< 0.001	44.37	14.05 to 74.70	0.005*
Femoral tunnel location (high–low)	7.6 ± 3.9	27.27	17.92 to 36.61	< 0.001	14.64	6.12 to 23.15	0.001*
Complications: Absent	6.1 ± 3.1	-	-	-	-	-	-
Complications: Present	9.3 ± 4.0	3.16	0.84 to 5.47	0.009	0.30	-1.29 to 1.89	0.702

CI, confidence interval; s.d., standard deviation; SNQ, signal noise quotient.

*, significant values.

In this study, graft SNQ correlated significantly with femoral and tibial tunnel locations and diameters, suggesting that intraoperative factors significantly affect graft healing. Ducouret et al. conducted a study comparing 3D MRI and 3D CT in the assessment of the tibial tunnel in patients with ACL reconstruction, in which they found the tunnel location in 3D MRI as 45% in the coronal plane and 49% in a sagittal plane which was similar in this study (mean tibial tunnel position in the AP direction 0.44 ± 0.05 and in the ML direction 0.45 ± 0.03).[9] Studies conducted by Oshima et al. and Ae O et al. showed a correlation between SNQ and tibial tunnel location in the ML direction and AP direction, respectively.[2,3] The femoral tunnel location in the current study was shallower (0.35 ± 0.05) and lower (0.39 ± 0.10) as compared to those observed by Oshima et al. and Ae O. et al. Both authors found a significant correlation between SNQ and a low femoral tunnel, while no significant correlation was seen between SNQ and the deep femoral tunnel.[2,3] Both of these findings are consistent with the results found in the current study. Femoral tunnel (10.14 ± 1.16) and tibial tunnel (11.01 ± 1.29) dimensions were slightly higher than those observed by Oshima et al., but showed a significant correlation with SNQ, in the present study, consistent with the result of Oshima et al.[3]

In the current study, there was a significant difference in SNQ in patients with and without complications. The SNQ was higher in patients with complications, suggesting that complications can slow down the healing process. There was also a significant difference in femoral tunnel diameter, tibial tunnel diameter and tibial tunnel location (AP) in the two groups. Increased rates of complications were associated with an increase in the diameters of tibial and femoral tunnels, and were more frequent in the anteriorly placed tibial tunnel (Table 6).

The mean GBA observed in this study was 33.87 ± 5.88°, which was much lower and outside the range as compared to previous studies on single bundle ACL reconstruction transportal technique, having the value in between 56° and 77°.[2,3,15] The decrease in the value of GBA was likely because of the variations in the surgical technique of femoral tunnel placement, as a posteriorly placed femoral tunnel exit shows a correlation with a lower GBA.[18] In the current study, it was seen that there was no significant association between SNQ and GBA, as well as, no significant correlation between GBA and other factors, which can also be because of differences in operative technique and other confounding factors. This was contrary to the results of Oshima et al. and Chen et al.[3,15]

The value of notch volume with respect to graft size has been highlighted recently.[2,3] It is seen that low residual volume of the intercondylar notch has been associated with raised SNQ, affecting graft healing. This implies that a greater residual notch volume should prevent wear and tear of the graft, promoting healing. However, it was observed that the thin configuration of the graft was associated with increased tear rates, and increasing the graft thickness caused a decrease in the residual intercondylar notch volume.[2,3] In this study, an attempt to find a correlation between notch volume and SNQ was conducted, however, no such correlation was found, similar to the findings reported by Oshima et al.[3] This could be because the graft volume was not taken into account, which can be studied further.

On application of multivariable regression analysis, the two factors independently affecting the SNQ were tibial tunnel location in the ML direction and femoral tunnel location in the HL direction, suggesting that a lower femoral tunnel and a laterally situated tibial tunnel were associated with higher SNQ levels. In the transtibial tunnel technique, the tibial tunnel location affects the femoral tunnel position and determines the orientation of the intra-articular graft.[4] However, with the transtibial technique, it may be difficult to place the tunnels within the native ACL footprint.[19] This leads to poorly positioned tunnels, which can cause abnormally increased traction force and graft impingement on the intercondylar notch roof.[20,21]

TABLE 6: Factors having a significant difference in patients with complications and without complications.

Variable	Parameter	Total	Complications		Difference		Significance	
			Present	Absent	%	95% CI	*t*	*p*†
SNQ (graft)	-	-	-	-	3.16	0.79– 5.53	2.714	0.011
	Mean ± s.d.	7.59 ± 3.86	9.29 ± 3.99	6.13 ± 3.14	-	-	-	-
	Median	6.60	9.78	5.57	-	-	-	-
	IQR	4.53–12.34	5.89–12.34	4.03–8.49	-	-	-	-
Femoral tunnel diameter (mm)	-	-	-	-	0.80	0.05–1.54	2.190	0.037
	Mean ± s.d.	10.14 ± 1.16	10.57 ± 1.31	9.78 ± 0.88	-	-	-	-
	Median	10.20	10.45	9.80	-	-	-	-
	IQR	9.12–11.33	9.67–11.33	8.90–10.40	-	-	-	-
Tibial tunnel diameter (mm)	-	-	-	-	0.87	0.06–1.68	2.192	0.035
	Mean ± s.d.	11.01 ± 1.29	11.48 ± 1.30	10.61 ± 1.17	-	-	-	-
	Median	11.00	11.35	10.90	-	-	-	-
	IQR	10.05–12.15	10.90–12.15	9.78–11.30	-	-	-	-
Tibial tunnel location (antero-posterior)	-	-	-	-	-0.03	-0.06 to −0.01	-2.548	0.015
	Mean ± s.d.	0.44 ± 0.05	0.42 ± 0.04	0.45 ± 0.05	-	-	-	-
	Median	0.42	0.41	0.44	-	-	-	-
	IQR	0.41–0.43	0.39–0.43)	0.42–0.48)	-	-	-	-

SNQ, signal noise quotient; s.d., standard deviation; CI, confidence interval; IQR, interquartile range.
†, the *t*-test was used to calculate the *p*-values.

Collectively, femoral tunnel and tibial tunnel locations correlated positively with independent factors that affect graft SI and SNQ. Other factors that correlated with SNQ were femoral tunnel diameter, tibial tunnel location (ML), tibial tunnel location (AP), femoral tunnel location (high – low) and tibial tunnel diameter. This showed that the major factors affecting SNQ and hence the graft healing were intraoperative factors, and a more anatomic approach with optimal graft size can produce a healthier graft.

Study limitations

This was a single-centre study with a small sample of 42 patients, which is difficult to extrapolate to the general population. An MRI scan was performed only once, so the variability of the findings as time passed was not studied. There was no baseline value for all the measurements. A difference in the activity level and other clinical details of patients was not taken into account, which may independently affect graft healing. It would be informative to know the appearance of these findings and their association with clinical and other intraoperative data on a larger study population, as this could add to the predictive and diagnostic value of MRI as a non-invasive tool for graft assessment.

Conclusion

Taking SNQ as the MRI predictor for graft healing, it was noted that there was an increase in the SNQ with an increase in the femoral and tibial tunnel diameter, a lower femoral tunnel, and an anteriorly placed tibial tunnel. There was an increase in the rates of complications noted with an increase in the SNQ levels of the graft. SNQ levels were highest at the proximal part of the graft, near its interface with the femoral tunnel, suggesting the slowest healing at that part of the graft. Two independent factors affecting SNQ of graft were recognised, that is, tibial tunnel location in the ML direction and femoral tunnel location in the high-low direction, which suggests that a lower femoral tunnel and a lateral tibial tunnel can be an independent cause of persistent increased SNQ and hence a slower process of graft healing. MRI can be effectively used to assess the in vivo well-being of the ACL graft. Intraoperative factors, predominantly the positions of the tibial and femoral tunnels, are the major factors affecting graft healing.

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Competing interests

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Authors' contributions

S.J. and C.R.R. were involved in the conceptualisation of the initial idea, as well as the study design, data collection, interpretation and article preparation. A.D. assisted with the study design, data collection and article creation. S.D. and M.R. were the principal and assistant operating surgeons, respectively, and provided samples. All authors provided critical feedback, helped shape the research, analysis and article, and approved the final version for submission and publication.

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Data availability

The data that support the findings of this study are available from the corresponding author, C.R.R., upon request.

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