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Original article

MRI assessment of growth disturbances after ACL reconstruction in children with open growth plates–Prospective multicenter study of 100 patients

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ABSTRACT

Introduction: We were interested in the consequences of anterior cruciate ligament (ACL) reconstruction on the growth plates and the impact on growth in children with open growth plates. The primary objective was related to growth disturbances with the null hypothesis being that ACL reconstruction in open growth plates does not cause any. The secondary objective related to the presence of physis lesions on MRI, with the null hypothesis being that ACL reconstruction in open growth plates does not induce any.
Material and Methods: In the context of a 2017 SFA symposium on ACL reconstruction with open growth plates, we conducted a prospective multicenter study with 2 years' follow-up. The study enrolled 100 patients; 71 were available for analysis. Four reconstruction techniques were used: semitendinosus-gracilis (STG), short graft (SG), quadriceps tendon (QT) and fascia lata (FL). MRI was used to look for growth disturbances as evidenced by deviation of the Harris lines or modification of the physis and diaphysis angles. Physis lesions were determined on MRI based on the presence of physeal bone bridges (PBB).
Results: No growth disturbances were found. However, PBBs were found in 14 patients (20%). At the femur, the relative risk (RR) was higher when a STG graft was used (RR = 2.1) and the tunnel diameter was ≥ 9 mm (RR = 1.7). Epiphyseal fixation had a higher risk than transphyseal fixation (RR = 1.6 vs. 1.2). At the tibia, the RR was higher when a QT graft was used (RR = 3.6), when screw fixation was performed (RR = 3.7) or when the graft did not fill the tunnel sufficiently (RR = 1.5).
Discussion: The absence of growth disturbances after 2 years' follow-up validates the possibility of ACL reconstruction with open growth plates, including with transphyseal techniques. The presence of small growth plate lesions such as bone bridges means that precautions should be taken with respect to tunnel trajectory, tunnel diameter, graft and tunnel diameter matching and graft fixation.
Level of evidence: III, prospective cohort study.

1. Introduction

Among the complications after anterior cruciate ligament (ACL) reconstruction, growth disturbances occur specifically in children and adolescents with open growth plates. This can have esthetic or functional consequences and can contribute to arthritis progression due to altered mechanical loading.

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Current practice surveys have found that 11% of American surgeons [1] and 3% of French surgeons [2] have encountered a serious growth disturbance after ligament reconstruction in children with open growth plates. The true incidence is lower in clinical studies. No cases of growth disturbances requiring reoperation were found in 8 patients with a mean follow-up of 5.8 years [3] and in 12 patients with a mean follow-up of 4.1 years [4]. In a more recent study, there were no cases in 27 patients with a mean follow-up of 10 years [5]. However, one study of 12 patients with 4.5 years' follow-up found two instances of accelerated growth with leg length discrepancy (LLD) [6]. Only one of these cases required epiphysiodesis surgery: this patient had repeat ACL surgery due to an early retear and epiphysiodesis corrected the problem. The other case had 16 mm of LLD, which was well tolerated. However, these studies had a limited number of patients. The largest study on this topic came from the 2006 SOFCOT (French Society for Orthopedic Surgery) symposium on ACL reconstruction in children [7]. There was 1 case of severe growth disturbance out of 92 patients (1%) at a mean follow-up of 3.5 years that required corrective surgery. This patient had 13° genu valgum at 18 months postoperative with lateral femoral epiphysiodesis revised by corrective osteotomy [8]. Minor subclinical problems in which the leg length or alignment are altered are more common, with 11 cases (12%) reported in the SOFCOT study [7] and 4 cases (33%) reported in the Koch study [6]. This real potential risk means that precautions must be taken with respect to tunnel placement and diameter relative to the growth plates and that this surgery should only be performed by experienced surgeons.

Of the three types of growth disturbances [9], type A (arrested) is the most problematic. It corresponds to stoppage of growth or epiphysiodesis due to damage to the physis or perichondral bone ring of Lacroix, which is attributed to tunnels, transphyseal screw fixation or periosteum removal at the bone ring. However, experimental studies have shown that if the tunnel diameter is less than 12% of the tibial physis diameter or 11% of the femoral diameter centrally, there are no growth disturbances [10]. Other studies suggested a threshold of 7% [11] or 7% to 9% [12]. Filling of the transphyseal tunnel by the tendon graft is protective [12,13], even if it does not prevent ossification bridges [14]. Type B (Boosted) corresponds to accelerated growth due to stimulation secondary to periosteum removal. Type C (deCelerated) is slowing of growth due to a tenodesis effect related to excessive tension on the graft, a mechanism that have been verified experimentally [15,16] and clinically [1,7].

In the absence of clinical and/or radiological consequences, an effect on the growth plates can be exposed using magnetic resonance imaging (MRI). At a mean follow-up of 36 months, Yoo et al. [17] found 5 physeal bone bridges (PBB) (4 tibial, 1 femoral) in a cohort of 43 patients operated using transphyseal fixation (12% rate) without alignment changes or clinical effects. No consequence or early physis closure was found on the MRI of 5 patients reviewed after 4.5 to 9.9 years' follow-up [18]. Higuchi et al. [19] reported thinning of the growth plates in 8 of 10 patients on comparative MRI images at 6 months' follow-up after transphyseal fixation, with no clinical consequences. Physis involvement is also described with extraphyseal fixation techniques as 8 small tibial lesions (affecting an average of 2.1% of the total physis area, and 6% in two cases) occurred in 15 patients with 24 months' follow-up; these also had no clinical consequences [20]. In an MRI study, Davis et al. [21] defined the safest epiphyseal tibial tunnel trajectory as being 27° to 30° depending on the patient's age and gender.

These observations led us to conduct a prospective study with MRI to determine the consequences of ACL reconstruction on the physes and its incidence on growth. The primary objective was to determine whether growth disturbances were present or not. The null hypothesis was that ACL reconstruction on open growth plates has no significant repercussion on growth. The main outcome was measurement of physis angles and Harris lines on MRI. The secondary outcome was the presence of growth disturbances on radiographs and clinical evaluation. The secondary objective was to determine whether physis lesions were present on MRI. The null hypothesis was that ACL reconstruction on open growth plates does not cause lesions. The outcome was the presence of PBBs, whether or not they caused epiphysiodesis.

2. Materials and methods

In the context of the 2017 Francophone Arthroscopy Society (SFA) symposium on ACL reconstruction in open growth plates, we carried out a prospective multicenter study with 2 years' follow-up. The study enrolled 100 patients between October 2015 and September 2017; 71 sets of patient records were complete, thus available for analysis (71%). Four reconstruction techniques were used: semitendinosus-gracilis (STG), short graft (SG), quadriceps tendon (QT) and fascia lata (FL). The mean patient age at the time of the procedure was 13.4 ± 1.7 years. MRI follow-up evaluations were scheduled for 6, 12, and 24 months postoperative. The MRI examination consisted of the usual sequences (T1, T2, PD fat-sat) and slices (sagittal and coronal). Only the operated leg was imaged on MRI. The search for growth disturbances was based on MRI measurement of deviation in the Harris lines (loss of parallelism relative to the growth plates) (Fig. 1) or change in angles between the diaphyseal axis and growth plate during successive MRI examinations (Fig. 2). These measurements were made on anteroposterior (AP) and lateral views of the femur and tibia, and between the femoral axis and Blumensaat line on a lateral view to look for any verticalization. A threshold value of 5° was used as a physiological difference between the first and last follow-up visits. In parallel, any radiological or clinical growth disturbances (LLD > 10 mm and/or

Fig. 1. View of Harris lines, here showing regular growth.

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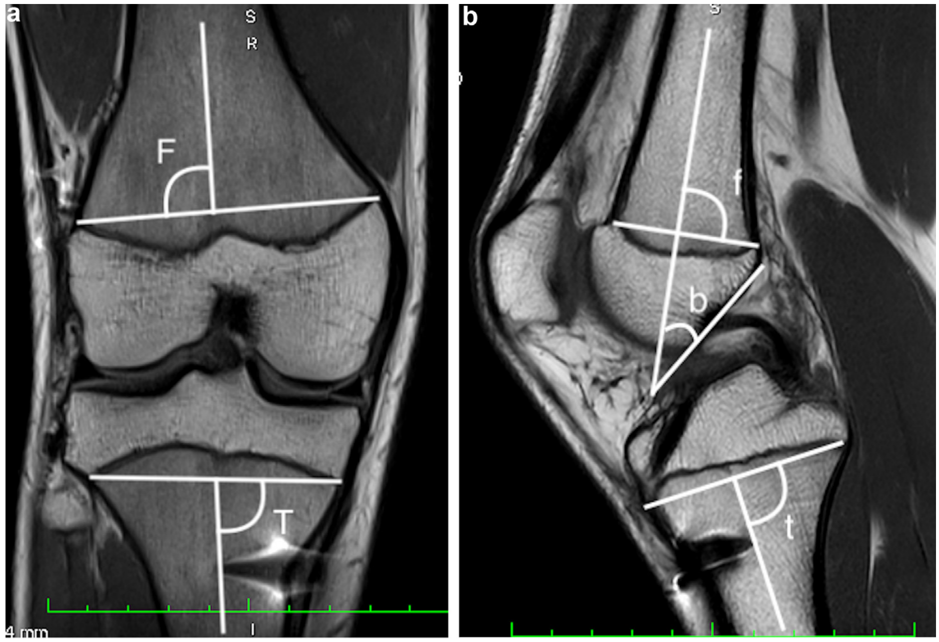

Fig. 2. Angle measurements on AP view (a) (femoral angle - F, tibial angle - T) and lateral view (b) (femoral angle - f, tibial angle - t, orientation of Blumensaat line - b).

misalignment > 5) were studied. The clinical functional assessment will not be discussed in this study. Evidence of physis lesions on MRI was based on finding PBBs (Fig. 3). We determined whether patient age, tunnel position and diameter, graft types, filling of tunnel by graft and fixation method had an impact on the occurrence of growth disturbances or PBBs.

Quantitative variables were compared using Student's t-test, while qualitative variables were compared using the Chi-square test with a 0.05 significance threshold. The effect of qualitative factors on the occurrence of growth disturbances or PBBs was expressed by calculating the relative risk (RR) and its 95% confidence intervals (95% CI); it was significant if the value of 1 was outside the interval. The statistical analysis was performed using StatEL software (www.adscience.eu).

3. Results

Of the 71 records analyzed, no clinical or radiological growth disturbance (LLD > 10 mm and/or misalignment > 5) was identified at 2 years' follow-up. The mean age of the patients at the 2-year follow-up was 15.8 ± 1.7 years. Twenty patients (28%) were still growing. Similarly, no growth disturbance (change in angles or Harris line deviation) was found in the MRI analysis. The angle values are shown in Table 1. The angle difference between the first and last follow-up examinations was 1.2 ± 2.3 on AP femur and 0.2 ± 1.7 on AP tibia, -0.7 ± 2.4 on lateral femur and -1.5 ± 3.0 on lateral tibia and 1.5 ± 2.3 for the Blumensaat line.

However, we found PBBs near the tunnels in 14 patients (20%): 8 in the femur (11%) and 10 in the tibia (14%) (Fig. 4). The mean age at the time of surgery for the patients who developed PBBs was 12.9 ± 1.4 years while those who did not had a mean age of 13.5 ± 1.7 years (not significantly different). The risk factors for PBBs are listed in Tables 2 and 3. Thus in the femur (Table 2), the RR of PBBs was higher if a STG graft was used and if the tunnel diameter $\geq$ 9mm. Epiphyseal fixation had a higher risk than transphyseal fixation. The risk was lower with a SG or FL over-the-top fixation. In the tibia (Table 3), the RR of PBBs was higher with QT grafts, screw fixation–the presence of hyperintensity around the screw (Fig. 5) was associated with a higher risk, independent of whether the screw was absorbable–and when the graft did not sufficiently fill the tunnel. The risk was lower when a SG or FL was used. None of the cases involved an epiphyseal tunnel. We found no threshold value for transphyseal tunnel diameter (mean 8 mm, range 6 to 10 mm). In 8 of the 71 patients, the tibial interference screw was transphyseal and had no effect on the occurrence of PBBs; the screw broke during growth in one patient (Fig. 6).

4. Discussion

While our study was prospective, the follow-up was only 2 years and 20 patients (28%) had not finished growing at the last follow-up visit, thus could still develop growth disturbances at some point in the future. While the clinical search for LLD was comparative, the MRI analysis was not, thus it may have missed subclinical involvement or thinning of the growth plates, as reported by Higuchi et al. [19] in 8 of his 10 patients.

At the 2-year follow-up, we found no significant change in the angles or deviation of the Harris lines on MRI, nor radiological or clinical changes (LLD > 1 cm and/or misalignment > 5). This confirms the primary objective of having no growth disturbances at 2 years postoperative, thus the possibility of performing ACL reconstruction in children with open growth plates. While 28% of the patients had not finished growing at the 2-year follow-up visit, major growth disturbances generally appear earlier [6,8]. Our findings are consistent with other published MRI studies [17,20], and also clinical reports where minor subclinical growth disturbances are described, while major growth disturbances requiring reoperation are rare [3,4,7]. This means that precautions should be taken when positioning and drilling the tunnels relative to the perichondral bone ring, and when tensioning the graft. These precautions are necessary to avoid stopping (type A) or slowing growth (type C). It is harder to prevent accelerated growth (type B) like in the Koch et al. study [6]; however, this condition is easy to correct by epiphysiodesis.

Our secondary objective was not attained. While ACL reconstruction on open growth plates did not affect growth, it causes

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Fig. 3. Femoral physeal bone bridge (a), magnified view (b).

physeal lesions such as PBBs. PBBs were found in 14 patients (20%) in our study in very specific locations. This finding is consistent with the Yoo study [17] (12% PBB rate) and with the experimental findings of Seil [14], even if the tunnel diameter is reasonable. We did not measure the percentage of physis crossed relative to the total physis area; however, Yoo [17] calculated it was less than 3% for the tunnels up to 11 mm. The tunnels in our study were not larger. This is well below the threshold values proposed by Jannarv et al. [12] and Makela et al. [11] with a lower limit of 7%. Various factors such as physis lesions due to heating related to overly fast rotation speed during tunnel drilling or excessive tension on the graft leading to a tenodesis effect are potential risk factors for PBBs [17]. Other risk factors emerged from our study, which serves as a reminder that while there was no impact on growth, the error margin is small, and vigilance is required, including for experienced surgeons.

We found a higher risk of PBBs in the femur when a STG was used (RR = 2.1), when the tunnel diameter was ≥ 9 mm (RR = 1.7) or when the tunnel was epiphyseal (RR = 1.6). The over-representation of STG grafts is likely related to tunnel diameter; we must keep in mind that a maximum of 9 mm was advocated based on the 2006 SOFCOT study [7]. An epiphyseal trajectory is also a risk factor, potentially due to damage to the epiphyseal side of the physis, which is more fragile than the metaphyseal side, or for transphyseal tunnels, being too close to the perichondral bone ring. It is important to stay 3 mm away from the bone ring as specified by Seil et al. [22] for tunnel drilling; radiographic detection is useful. It is also important to remember that the physis is not the only growth plate and that an epiphyseal tunnel can have an effect on the epiphyseal cartilage. This likely has no consequences in adolescents, since this cartilage is already ossified, but is a possibility in younger children. The significantly lower risk in the femur for the SG (RR = 0.5) even though the tunnels are transphyseal, is probably related to the reasonable tunnel diameter and optimal filling of this tunnel since the graft must always bridge the physis. The over-the-top nature of a FL graft is protective (RR = 0).

At the tibia, the risk of PBBs was significantly higher when a QT graft was used (RR = 3.6); this is closely related to use of interference screws for fixation as opposed to the graft itself. In fact, interference screw fixation (RR = 3.7) increases the risk and the presence of a hyperintense signal around the screw (RR = 2.4)—often associated with PBBs—may reflect the changes in local stresses related to this screw, whether or not it is absorbable (RR = 1.2). Consequently, interference screws should be placed as far as possible from the physis, especially by lengthening the tunnel to make it more vertical, which results in the tunnel's cross-section being less oval at the physis and thus reducing the area. Insufficient filling of the tunnel by the graft (RR = 1.5) is also a known risk factor [13] [12]. This means we must carefully match the diameter of the graft with that of the tunnel [17]. It is logical to avoid transphyseal screw positioning, even if this had no effect in our study (RR = 1). Placement just below the physis is not ideal, either due to changes in the local stresses as described above, or by decentering the graft in the tunnel at the physis level, which reduces filling and thus increases the risk of PBBs. The lower risk at the tibia when using a SG (RR = 0.3) is likely related to the type of fixation—a button resting on the metaphyseal cortex—which in preferable in our opinion. Filling of the tunnel and bridging of the physis by the graft are essential, and the graft must not be too short. With a FL graft, the tibial epiphyseal trajectory appears to be protective relative to the risk of PBBs (RR = 0, $p < 0.05$), even if a minor lesion is possible [20]. This means we must pay attention to the trajectory and especially its angle, which must be between 27° and 30°, depending on the patient's age and gender

Table 1
Mean angle values and differences.

Mean angle in degrees/SD	AP femur (F)	AP tibia (T)	Lateral femur (f)	Lateral tibia (t)	Blumensaat b
First follow-up	84 ± 2	81 ± 4	89 ± 3	86 ± 6	40 ± 5
Last follow-up	86 ± 3	81 ± 5	88 ± 3	81 ± 5	40 ± 5
P	NS	NS	NS	NS	NS
Difference	1.2 ± 2.3	0.2 ± 1.7	−0.7 ± 2.4	−1.5 ± 3.0	1.5 ± 2.3

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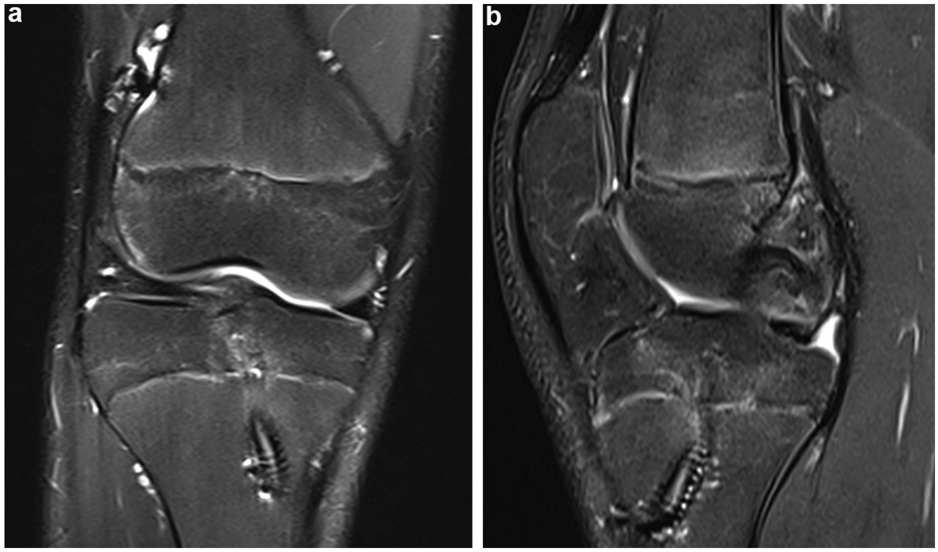

Fig. 4. A 12½-year-old male patient who underwent ACL reconstruction with an STG graft. Tibial bridge on AP view (a), lateral view (b) and femoral bridge on lateral view (c). No effect on growth at 2 years' follow-up.

Fig. 5. An 11-year old male patient who underwent ACL reconstruction with an STG graft. Hyperintense signal around the absorbable tibial interference screw on AP view (a) and lateral view (b). Tibial bone bridge on AP view (c). No effect on growth at 2 years' follow-up.

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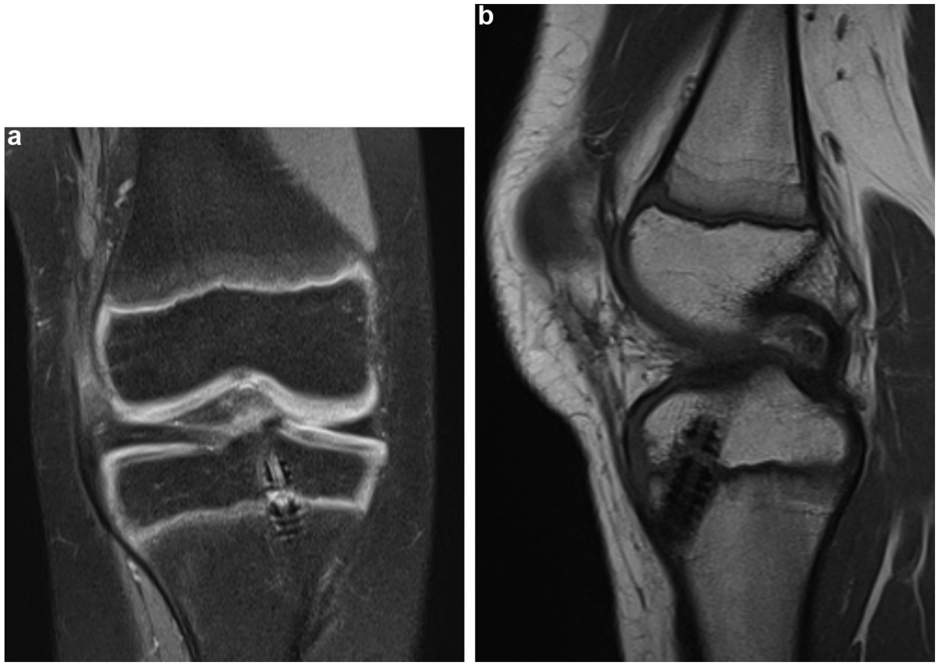

Fig. 6. A 12-year-old female patient who underwent ACL reconstruction with a QT graft. Absorbable interference screw bridges the physis. While the screw broke and migrated, there was no consequence for growth at the 2-year follow-up.

Table 2
Relative risk of the occurrence of physeal bone bridges at the femur.

Parameter	RR and 95% CI	*p*
STG	2.1 [0.6–7.6]	NS
SG	0.5 [0.1–2.1]	< 0.05
QT	0.8 [0.1–5.7]	NS
FL	1.3 [0.2–9.1]	NS
Tunnel Ø ≥ 9 mm	1.7 [0.3–9.2]	NS
Epiphyseal tunnel	1.6 [0.4–5.9]	NS
Transphyseal tunnel	1.2 [0.2–6]	NS
Over-the-top	0	< 0.05

Table 3
Relative risk of the occurrence of physeal bone bridges at the tibia.

Parameter	RR and 95% CI	*p*
STG	1.4 [0.4–4.5]	NS
SG	0.3 [0.1–1.5]	NS
QT	3.6 [1.2–10.8]	< 0.05
FL	0	< 0.05
Epiphyseal tunnel	0	< 0.05
Screw fixation	3.7 [0.8–16.1]	NS
Hyperintensity/screw	2.4 [−0.3–7.7]	NS
Non-absorbable screw	1.2 [0.3–5.3]	NS
Transphyseal screw	1 [0.3–3.6]	NS

[21]. Here again, radiographic determination of the physis location should be carried out. We did not identify a threshold value for the tibial tunnel diameter; all the tunnels in our study were less than 10 mm, which appears to be the maximum.

5. Conclusions

The absence of growth disturbances at the 2-year follow-up visit in our study validates the possibility of performing ACL reconstruction in children with open growth plates, even by transphyseal techniques. The presence of small physeal lesions such as PBBs—while they had no consequences in our study—means that precautions should be taken when setting the tunnel trajectory relative to the growth plates, their diameter should not exceed 9 mm (especially at the femur), the graft and tunnel diameters must match, and graft fixation methods. These techniques of ACL reconstruction in patients with open growth plates should only be performed by surgeons familiar with the risks of altering growth and who know how to prevent them and treat them.

Disclosure of interest

The authors declare that they have no competing interest.

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None.

Authors' contribution

Philippe Gicquel: data collection and analysis, writing of the article.
Loïc Geffroy: data collection and analysis.
Henri Robert: data collection and analysis.
Matthieu Sanchez: data collection and analysis.
Jonathan Curado: data collection and analysis.
Franck Chotel: data collection and analysis, reading of the article.
Nicolas Lefevre: data collection and analysis, reading of the article.

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