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An evaluation of 1654 premolars transplanted in the posterior region—A retrospective analysis of survival, success and complications

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Abstract

Aim: The aim of this retrospective analysis was to evaluate the survival, success and possible complications of transplanted premolars in the posterior region subdivided by developmental stage and patient age.

Materials and Methods: This study included patients who underwent tooth transplantation between April 2004 and December 2021. A total of 1654 premolars were transplanted into 1243 patients. Tooth mobility, oral hygiene and periodontal parameters were clinically evaluated. Intraoral radiographs were used to evaluate pulpal and periodontal healing, and root formation. The cumulative survival rate was calculated using the Kaplan–Meier method.

Results: Data were subdivided into three groups based on the stage of root development and patient age. The mean age at surgery was 14.5 years. The main indication for transplantation was agenesis, followed by trauma and other indications, such as impacted or malformed teeth. A total of 11 premolars were lost during the study period. The overall survival and success rates in the immature premolar group after an observation period of 10 years were 99.7% and 99.4%, respectively. High survival and success rates (95.7% and 95.5%, respectively) were also observed when fully developed premolars were transplanted into the posterior region of adolescents. In adults, the success rate after 10-year follow-up is 83.3%.

Conclusions: Transplantation of premolars with developing and fully developed roots is a predictable treatment modality.

KEYWORDS
autotransplantation, dental trauma, missing teeth, tooth agenesis

1 | INTRODUCTION

Autotransplantation is the procedure of grafting a tooth from its original position to a deficient zone in the mouth in the same individual. The transplanted tooth can be placed at either an extraction site or in a surgically prepared socket.[1] Autotransplantation offers a relatively low-cost solution with a favourable aesthetic outcome. In contrast to osseointegrated implants, transplanted teeth have a vital periodontium and, therefore, have the capacity for functional adaptation, rebuilding of a normal alveolar ridge and continued alveolar bone remodelling during growth in children and adolescents.[2–4]

Autotransplantation is a well established treatment option for growing individuals with missing teeth.[5] Treatment of a young patient population is challenging, as changes in the oral cavity due to their development in time should be considered. Congenitally missing teeth; non maintainable traumatised teeth; teeth with poor prognosis due to periodontal, restorative and/or endodontic reasons; and teeth with developmental abnormalities or transplantation of impacted teeth to their normal position (transalveolar transplantation) are the most common indications.[6,7]

Autotransplantation is considered successful when regeneration of the periodontal ligament occurs and physiologic mobility is present with an absence of signs of progressive root resorption. In cases of teeth with open apices, pulp revascularisation and the achievement of sufficient root length to support continued tooth function are also considered important factors in defining success. This translates into enhanced aesthetics, function and integrity of the dental arch.[8]

The first documented case report of autogenous tooth transplantation was described by Fauchard in 1728 in his book Le Chirurgien Dentiste.[9] In 1974, Slagsvold and Bjercke published the first surgical protocol for transplantation of immature premolars.[10] In 1990, Andreasen et al. published a series of scientific papers on 370 autotransplanted premolars with a 13-year follow-up period. They standardised the surgical technique, analysed the prognostic factors that influenced the success, and reported a 95% survival rate in teeth with an open apex.[11] Since then, a substantial number of studies have been published on this topic, which report success and survival rates ranging from 61% up to 100%.[12]

The outcome of tooth transplantation can be influenced by several factors. Donor tooth type, root anatomy and stage of root development, recipient tooth site, status of the recipient site, surgeon experience and technique used, duration of stabilisation and method used, type of follow-up care and orthodontic treatment after transplantation are among the factors to consider. However, the evidence is unclear on which of the aforementioned factors is the most important determinant of success.[13,14]

According to literature, premolars constitute the majority of transplanted teeth, followed by molars, canines, incisors and supernumerary teeth. The replacement of congenitally missing premolars, especially in the lower jaw, with crowding in the opposing arch is the most common indication for tooth transplantation. Therefore, most published studies refer to the transplantation of premolars in the posterior region; however, the sample size is limited. The aim of this retrospective analysis was to evaluate the survival, success and possible complications of transplanted premolars in the posterior region subdivided by developmental stage and patient age.

2 | MATERIALS AND METHODS

2.1 | Source of data and participants

This was an observational retrospective analysis. Checklists for reporting items specific to observational studies using routinely collected health data (STROBE and RECORD) were used.[15]

The population consisted of patients who were referred from various orthodontic, paediatric and general practices to a clinic specialising in periodontology during a 17-year period of 17 years from 1 April 2004 up to 31 December 2021. Patients included in the retrospective analysis had to be in good general health at the time of surgery (i.e. not suffering from any disease that might influence postoperative healing) and not suffering from a new traumatic dental injury affecting the transplanted tooth during the observation period.

All procedures performed in relation to the treatment of patients were in accordance with the 1964 Helsinki Declaration and its later amendments. The data obtained were anonymised and consequently de-identified irreversibly. Therefore, it is impossible to reveal information related to a specific individual. The informed consent was obtained in advance, provided permission for data related to the patient treatment to be used anonymously for further analysis.

The workflow used in these patients was a modification of what Andreasen et al.[11] introduced based on the indication, development of the donor tooth and recipient tooth site.

2.2 | Presurgical phase

The presurgical examination included a detailed medical questionnaire, and clinical and radiographic assessments. The intraoral examination consisted of assessment of various periodontal parameters, evaluation of the patient's level of oral hygiene and inspection for caries. In cases of periodontal disease, oral hygiene instructions, reenforcement and appropriate periodontal therapy were provided before surgery.

During the preoperative evaluation of potential donor teeth, the stage of root development was radiographically evaluated using the rating of Moorrees et al.[16] Based on this classification, root development was divided into the following categories: Stages 1–4 (one to four quarters of the anticipated root length with an open apical foramen), Stage 5 (four quarters of the root length and a half-closed apical foramen), Stage 6 (four quarters of the root length and constricted apical foramen) and Stage 7 (four quarters of the root length and closed apical foramen). The donor teeth with a root development of Stage 3, 4, 5 and beginning Stage 6 were transplanted with the objective to pursue revascularisation.[17] When root development was beyond Stage 6 or 7, the chance of revascularisation was deemed minimal to none.[18] In this case, to prevent inflammatory resorption due to necrotic pulp tissue, endodontic treatment was performed preferably preoperatively and on average 6 weeks prior to transplantation. If endodontic treatment of the donor tooth was not feasible preoperatively, the procedure was performed 2 weeks postoperatively. The endodontic treatment was performed by an endodontist and included debridement of the root canal followed by obturation with thermoplasticised gutta-percha.[19,20]

From 2017, the protocol was slightly modified in the sense that the fully developed donor teeth were orthodontically preloaded with an extrusive force on average 2–4 weeks prior to transplantation, to stimulate the periodontal ligament and increase cell proliferation to facilitate extraction. In addition, the protocol was

implemented with the prescription of antibiotic prophylaxis 1 h before transplantation, as described by Andreasen et al.[11] in the case of teeth beyond Moorrees' Stage 4 root development and/or in the case of pronounced periapical or periodontal inflammation at the recipient site.

2.3 | Surgical procedure

In most cases, transplantation is performed under local anaesthesia. In six cases, premedication (Valium 0.5 mg/kg) was administered, while one patient was treated under general anaesthesia.

Two experienced periodontists (AL and DB) accredited by the Dutch Society of Periodontology (NVvP) followed a standardised surgical procedure. The detailed surgical protocol can be found in Appendix S1.

2.4 | Post-operative follow-up

The sutures were removed 1 week after surgery, and the patients were instructed to use a soft surgical toothbrush immersed in chlorhexidine twice daily for 2 weeks to clean the clinical crown of the transplant.

For the post-operative follow-up, the protocol used for avulsed teeth was applied.[21] Patients were reviewed at 3 and 6 weeks and 3, 6 and 12 months postoperatively. Thereafter, the patients were followed up at 12-month intervals.

The clinical recordings consisted of gentle periodontal probing at six sites, bleeding on probing and tooth mobility. Oral hygiene was critically evaluated at every follow-up visit and reinforced when necessary. For radiographic evaluation, periodontal ligament space formation, root development and pulpal healing were assessed. Obliteration is considered a sign of revascularisation. The intraoral radiographs (SorodexTM, Tuusula, Finland; DigoraTM, Strasbourg, France) were made using standard film holders (Rinn XCP film holding system®, Dentsply Sirona, Charlotte, NC, USA).

During the first two follow-up visits (3 and 6 weeks after surgery), gentle periodontal probing was used to evaluate periodontal tissue healing. The probing pocket depth at the six sites and bleeding upon probing were evaluated and recorded. Normal brushing was reinitiated in shallow pockets. The patients were also instructed to start using the transplanted tooth for normal function. When compromised healing was observed with the formation of deep pockets (>5 mm, depending on the vertical position of the transplant), pronounced bleeding on probing, and/or suppuration, a combination of antibiotics was prescribed (based on the weight of the patient, a combination of amoxicillin and metronidazole three times daily for 7 days).

During the 6-week control period, special attention was paid to the signs of inflammatory root resorption. In cases of uneventful healing after 6 weeks, the transplants were functionally loaded either by placement of the orthodontic appliance within 2 weeks, or if orthodontic treatment was not indicated, and if no spontaneous eruption of the transplant was observed, with a composite resin occlusal build-up.[22,23]

2.5 | Data collection

Patient demographic data, such as sex, age and smoking habits, were extracted from patient records, including the following variables:

1. Donor tooth
   - Tooth type
   - Stages of root development, according to Moorrees et al. (1963)[16]
   - Number of roots
2. Recipient site
   - Position of recipient site
   - Presence or absence of periapical or periodontal inflammation
   - Presence or absence of predecessor
3. Endodontic treatment timing: preoperatively or postoperatively.
4. Causes of tooth loss that initiated treatment with a tooth transplant, such as trauma, agenesis, caries, endodontic complications and tooth impaction/retention.
5. Antibiotic coverage, timing and type of antibiotics used.

The healing was evaluated based on clinical and radiographic assessments as follows:

1. Clinical parameters
   - Probing pocket depth
   - Bleeding on probing
   - Tooth mobility/percussion sounds (absence of tooth mobility and/or high metallic percussion sounds) were considered indicative of ankylosis.
2. Radiographic assessment
   - Formation of the periodontal ligament including an intact lamina dura around the entire root: Changes in width of the periodontal ligament was considered a sign of unfavourable healing. Signs of replacement resorption (ankylosis) were recorded as indicating unfavourable healing. Effectively treated surface resorption with endodontic treatment were considered favourable.
   - Obliteration of the pulp and continued root formation: Pulpal inflammation and necrosis were considered to have occurred when the transplanted teeth exhibited periapical radiolucency or resorption. If no signs of obliteration were observed, the apical zone was closely monitored for periapical radiolucency or clinical signs of inflammation. Pulp canal obliteration was recorded according to the classification of Jacobsen and Kerekes (1977).[24]

Success of the transplantation was evaluated using the following criteria:

- Teeth with immature root formation showing a completed root formation following transplantation.

TABLE 1 The total number of premolars transplanted to the posterior region from 2004 to 2022, subdivided into three groups based on root development and age.

					Indication			Recipient site		
	N	Mean age (range)	Sex	Smoking	Agenesis	Trauma	Other	Tooth present	Edentulous	Impacted tooth
Posterior	1654	14.5 (9.3–65.2) years	♀ 57.7%; ♂ 42.3%	0.2%	1575	9	72	1371	270	15
Immature	1190	12.7 (9.3–20.1) years	♀ 58.7%; ♂ 41.3%	0%	1159	4	27	1034	142	14
Mature <18 years	368	14.9 (11.4–18) years	♀ 51.6%; ♂48.4%	0%	357	2	9	299	68	1
Mature ≥18 years	96	35.1 (18.2–65.2) years	♀ 70.8%; ♂ 29.2%	4.2%	57	3	36	36	60	0

- Successful endodontic treatment was performed in immature teeth with pulpal necrosis after transplantation, or in teeth with complete root development.
- Favourable periodontal healing with absence of deep pockets and normal tooth mobility
- In case of root resorption: successful treatment of the resorption.

2.6 | Data management and statistical analysis

The data were analysed using SPSS (Version 25; IBM Corp. Armonk, USA) for statistical analysis. Descriptive analyses, including means and ranges, were performed. The cumulative survival rate was calculated using the Kaplan–Meier method. To present the collected data in a comprehensible manner, the data were subdivided into three groups. First, the division was based on the stage of root development as either incomplete (up to Moorrees' Stage 6) (immature group, IMRD) or complete root formation (beyond Moorrees' Stages 6 and 7) (mature group, MRD). Subsequently, the mature group was subdivided based on patient's age in a group below 18 years of age (MRD <18 years) and a group of 18 years of age or older (MRD ≥18 years). The results were considered statistically significant at a p-value <.05.

3 | RESULTS

A total of 1654 premolars were transplanted during a 17-year period into the posterior region in 1243 patients (Table 1). Twenty-two patients were excluded from the analysis: 14 patients did not comply with the post-operative protocol, two patients had a traumatic injury to the transplanted tooth and six patients did not give permission to use their data. The average patient's age was 14.5 years with a range of 9.3–65.2 years; 57.7% of the patients were female. Among the MRD ≥18-year group, 4.2% of the patients were smokers.

The main indications for transplantation were agenesis ($n=1575$) followed by trauma ($n=9$), and impacted or malformed teeth ($n=72$). A predecessor was present in most recipient sites ($n=1371$). According to the criteria of Moorrees et al.,[16] 1190 premolars (72%) had an open apex, whereas 464 premolars (28%) had fully developed roots. Of the 464 premolars with completed root formation, 368 premolars were transplanted in the MRD <18-year group and 96 premolars were transplanted in the MRD ≥18-year group.

3.1 | Donor teeth

In all three groups, the upper second premolar was the most commonly used donor tooth, with a range of 37.5–49.7% (Table 2). First upper premolars were the least frequently transplanted (0.2%–2.1% of the cases). Most predominant were Moorrees' Stages 4 (49.8%) and 5 (39.7%) of root development. In donor teeth with a complete root formation, the endodontic treatment was performed before the transplantation in more than 90% of the cases.

3.2 | Recipient sites

Table 3 presents the distribution of the recipient sites. The most frequent recipient site in all groups was the position of the lower second premolar (93.3%, 91.3% and 47.9%, respectively). Molar sites were the least common (2.5% for all groups).

3.3 | Failures

Table 4 presents a detailed overview of failed transplants. A total of 11 transplants were lost during the observation period. Three transplants were lost in the immature group, whereas eight were lost in the mature group (four in each group). Four transplants had to be removed within the 1st year, whereas the remaining seven transplants survived between 1.5 and 7.5 years before extraction. Progressive root resorption is the most common cause of transplant loss.

3.4 | Complications

The complications can be divided into endodontic and periodontal complications.

TABLE 2 Type of donor teeth to the posterior presented based on root development stage and age group.

		Donor teeth								Root development Moorrees' stage			
	Total	14	15	24	25	34	35	44	45	3	4	5	6
Immature	1190	2 (0.2%)	554 (46.6%)	6 (0.5%)	591 (49.7%)	0 (0%)	14 (1.2%)	0 (0%)	23 (1.9%)	1.6%	49.8%	39.7%	8.9%
										Endodontic treatment before transplantation		Endodontic treatment after transplantation	
Mature < 18 years	368	3 (0.8%)	172 (46.7%)	3 (0.8%)	179 (48.6%)	1 (0.3%)	1 (0.3%)	2 (0.5%)	7 (1.9%)	97.3%		2.7%	
Mature ≥ 18 years	96	1 (1%)	37 (38.5%)	2 (2.1%)	36 (37.5%)	3 (3.1%)	7 (7.3%)	3 (3.1%)	7 (7.3%)	92.7%		7.3%	

TABLE 3 Location of the recipient site in the posterior region presented based on root development stage and age group.

		Location recipient site							
		Premolars				Molars			
		Upper		Lower		Upper		Lower	
	N	First	Second	First	Second	First	Second	First	Second
Immature	1190	11 (0.9%)	33 (2.8%)	26 (2.2%)	1110 (93.3%)	1 (0.1%)	0 (0%)	9 (0.8%)	0 (0%)
Mature < 18 years	368	7 (1.9%)	10 (2.7%)	11 (3%)	336 (91.3%)	0 (0%)	0 (0%)	3 (0.8%)	1 (0.3%)
Mature ≥ 18 years	96	6 (6.3%)	12 (12.5%)	6 (6.3%)	46 (47.9%)	5 (5.2%)	0 (0%)	19 (19.8%)	2 (2.1%)
Total	1654	24 (1.5%)	55 (3.3%)	43 (2.6%)	1492 (90.2%)	6 (0.4%)	0 (0%)	31 (1.9%)	3 (0.2%)

TABLE 4 Transplanted teeth lost within the observation period from 2004 to 2022.

Autotransplant failures												
	Sex	**Age at transplantation**	**Smoking**	**Indication**	**Donor tooth**	**Moorrees**	**Recipient site**	**Type recipient**	**Antibiotics**	**Tooth removal**	**Survival**	**Complications**
Immature												
	F	15 y 5 m	no	Impaction	15	4	35	tooth present	post-transplantation	11/06/2020	2 m 4 w	External cervical root resorption (due to inflammation)
	M	12 y 5 m	no	Agenesis	25	5	35	tooth present	Prophylaxis	11/02/2020	1 y 6 m	Replacement resorption (ankylosis)
	F	11 y 5 m	no	Agenesis	25	5	35	tooth present	None	15/12/2021	1 y 7 m	Replacement resorption (ankylosis)
<18 years						Endodontic treatment						
	F	17 y 11 m	no	Agenesis	15	before transplantation	45	tooth present	None	05/03/2020	2 y 9 m	Replacement resorption (ankylosis)
	M	14 y 6 m	no	Agenesis	15	before transplantation	45	edentulous	None	25/10/2006	1 m 3 w	Surgical complication (infection bone rebuild by oral surgeon)
	F	16 y 5 m	no	Agenesis	15	before transplantation	45	edentulous	post-transplantation	05/07/2021	5 y 2 m	Replacement resorption (ankylosis): late functional loading >3 months
	M	14 y 10 m	no	Agenesis	25	before transplantation	34	edentulous	None	16/11/2020	2 y 2 m	Replacement resorption (ankylosis)
≥18 years												
	M	65 y 2 m	no	Impaction	44	after transplantation	15	edentulous	post-transplantation	30/10/2020	11 m 2 w	Replacement resorption (ankylosis)
	M	44 y 1 m	no	Impaction	15	before transplantation	36	edentulous	post-transplantation	26/09/2016	1 m 3 d	Compromised healing in first 3 weeks
	F	23 y 7 m	no	Agenesis	15	before transplantation	45	tooth present	None	30/11/2021	6 y 10 m	Replacement resorption (ankylosis)
	M	37 y 3 m	yes	Agenesis	25	before transplantation	44	edentulous	None	19/07/2017	7 y 6 m	Late functional loading (>3 months): ankylosis, caries

3.5 | Endodontic complications

Endodontic complications were only observed in the IMRD (Table 5). Early complications, defined as inflammatory root resorption due to disturbed revascularisation, were observed within the first 6–9 months post-transplantation. In total, 11 cases of endodontic complications were recorded on average 4.1 months after transplantation, of which only one transplant was lost. In most cases, endodontic treatment results in the resolution of the inflammatory process and further uneventful healing. Most complications were observed in transplants with Moorrees' 6 root development.

When antibiotic prophylaxis was prescribed 1 h before transplantation, as described by Andreasen et al.,[11] the percentage of complications in endodontic healing was reduced from 8.5% without antibiotic prophylaxis to 2% in cases of prophylactic use of antibiotics. The highest reduction was observed in donor teeth with Moorrees' Stage 5 and 6 root development (12.2% without antibiotic prophylaxis vs. 2.9% after use of antibiotics) (Table 6).

Late complications, including apical radiolucency, were observed in 26 transplants at 5.9–118.9 months (approximately 10 years) post-transplantation. The stage of root development at the time of transplantation did not influence the prevalence of late endodontic complications. All late complications were successfully managed with endodontic treatment.

3.6 | Periodontal complications

Periodontal complications, defined as periodontal membrane distortion leading to replacement resorption and ankylosis, are shown in Table 7. Periodontal complications were observed in all groups: in total 67 cases were observed (4%) of which 27 in the IMDR group, 30 in the MRD <18-year group and 10 in the MRD ≥18-year group. The highest rate of ankylosis was observed in MRD <18-year group. Replacement resorption was determined by infraocclusion, radiographic loss of the lamina dura and a highly metallic percussive sound. The time point of diagnosis was 20–412 days after transplantation. Insufficient or delayed orthodontic loading is the primary cause of periodontal membrane distortion, followed by disturbed periodontal healing and surgical trauma.

Of the 67 ankylotic premolars, 61 were carefully luxated, two were removed and successfully replaced by another transplant, while in four cases, no luxation was performed. In most cases, the luxation results in normal mobility. Radiographically, the periodontal ligament space was normal. Luxation was unsuccessful in 10 patients.

3.7 | Survival and success analysis

The follow-up period was 10 years (Figure 1). A total of 1066 transplants were available for analysis after 1 year (788 in the IMRB group, 215 in MRD <18-year group and 63 in the MRD ≥18-year group, respectively). After 3 years, 354 transplants were available for analysis (260, 63 and 31 in each group, respectively), whereas after 5 years, 121 transplants were available (85, 23 and 13 in each group, respectively). After 10 years, 14 transplants were available for analysis (10, two, and two transplants in each group, respectively). The Kaplan–Meier test was used for analysis.

Figure 2 presents the survival and success analyses of the premolars with developing roots (IMRD group); 1190 premolars were available for analysis. Ten premolars presented with complications (seven in the 1st year and three in the 2nd year of follow-up), while five premolars were lost (two in the 1st year and one in 2 years after transplantation).

TABLE 5 Endodontic complications as divided into early complications (inflammatory resorption) and late complications (apical inflammation).

Endodontic complications									
			Endodontic treatment after	Age		Moorrees' Stage			
	Complication	N	Mean in months (range)	Years	Sex	4	5	6	Tooth loss
Immature	Inflammatory resorption	11	4.1 (1.4–7.5)	13 (11.5–15.4)	♀77% ♂ 23%	1	3	7	1
	Apical inflammation	26	33.7 (5.9–118.9)	13.3 (11.1–16.3)	♀ 46% ♂54%	7	9	8	0

TABLE 6 Comparison of the use of endodontic prophylaxis amoxicillin (3 Gr) in two groups: indication before and after June 2016.

Comparison efficacy of endodontic healing						
Groups	t	*N*	Prophylaxis	N complications	% complications	Tooth loss
All immature	Before June 2016	200	1	17	8.5%	0
	After June 2016	990	400	20	2%	1
Moorree's Stage 5 and 6	Before June 2016	123	1	15	12.2%	0
	After June 2016	455	331	13	2.9%	1

TABLE 7 Periodontal complications presented per subgroup and root development.

	Autotransplant periodontal membrane distortion/ankylosis											
							Age		Antibiotics			
	Complication	N	Diagnosis after transplantation	Luxation Yes	Luxation No	Luxation after transplantation	Years	Gender	Yes	No	Permanent ankylosis	loss
Immature	Surgical trauma	1	111 days (111–111)	1	0	202 days (202–202)	16.6 (16.6–16.6)	♀ 100% ♂ 0%	0%	100%	0	0
	Periodontal infection with root resorption	3	263 days (188–355)	3	0	314.7 days (237–441)	13.6 (12.6–15.4)	♀ 33% ♂ 67%	67%	33%	2	0
	Late/low/improper orthodontic forces	27	163 days (28–412)	26	1	260 days (49–770)	12.9 (10.3–15.3)	♀ 37% ♂ 63%	15%	85%	5	0
Mature <18 years	Delayed periodontal healing/surgical trauma	5	211.6 days (83–337)	5	0	292.8 days (125–429)	15.7 (14.9–17.1)	♀ 100% ♂ 0%	80%	20%	2	0
	Late/low/improper orthodontic forces	25	148.3 days (20–364)	24	1	214.4 days (41–607)	15.3 (13.8–18)	♀ 40% ♂ 60%	24%	76%	4	2
Mature ≥18 years	Delayed periodontal healing/surgical trauma	5	215.3 days (87–371)	3	2	415.3 days (203–777)	35.5 (20.3–51.2)	♀ 60% ♂ 40%	100%	0%	3	0
	Late/low/improper orthodontic forces	5	178.6 days (58–378)	5	0	291.8 days (157–405)	34.4 (21.2–50)	♀ 40% ♂ 60%	40%	60%	2	0

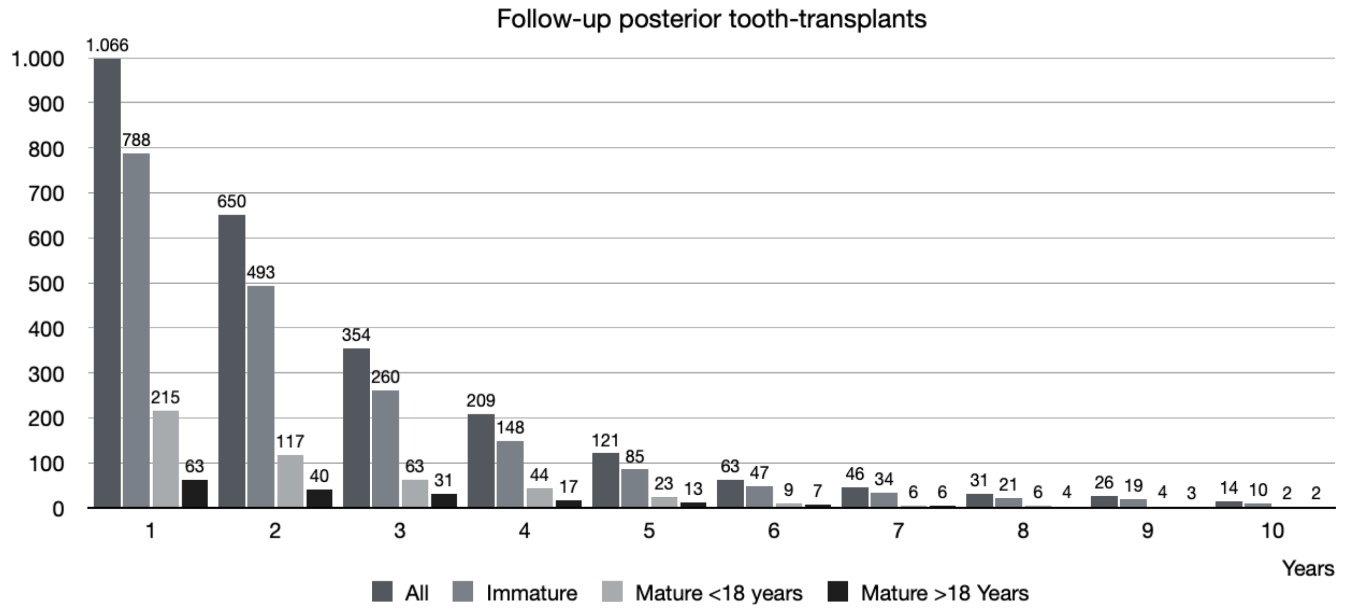
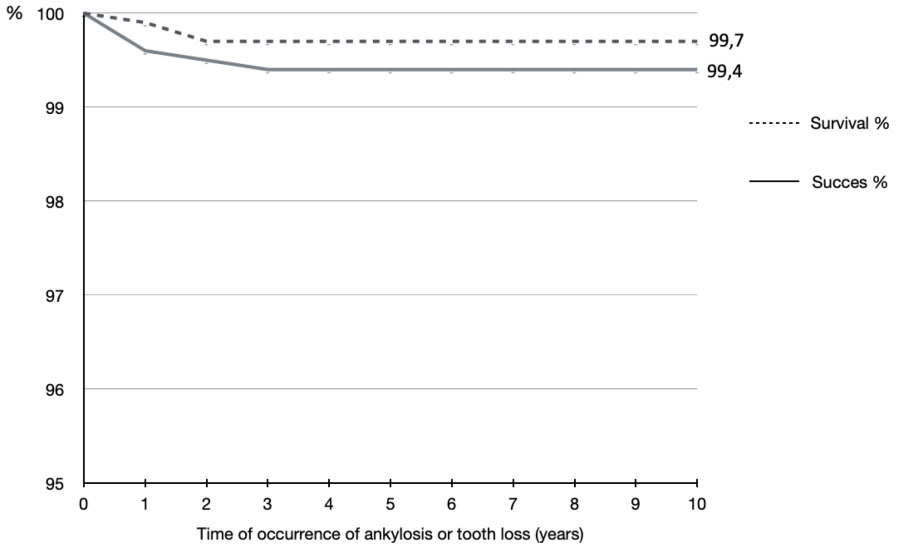


FIGURE 1 Follow-up from 1 year of tooth transplants to the posterior for all and presented based on root development stage and age group.

FIGURE 2 Kaplan–Meier survival and success analysis for immature tooth transplants.



The overall survival and success rates in this group after a 10-year observation period were 99.7% and 99.4%, respectively.

In the MRD <18-year group, 368 premolars were analysed (Figure 3). Over a period of 10 years, four premolars were lost, and 11 complications were observed (10 within the 1st year and one after 6 years). Therefore, the survival rate after 10 years was 95.7%. Success was calculated at 95.5%.

In the MRD ≥18-year group, 96 premolars were available for analysis (Figure 4). In total, four premolars were lost (two within the 1st year and two almost 7 and 8 years after transplantation). At the 6-year follow-up, the survival was 97.5%. Because of the late losses 7 and 8 years after transplantation and the very low number of transplants that were available for analysis, the survival percentage dropped to 83.3% after 10 years. In total, nine complications were observed: five occurred in the 1st year after transplantation and four occurred at 2, 5, 7 and 8 years after transplantation. Therefore, the success rate after 10 years was 83.3%.

4 | DISCUSSION

In the present retrospective analysis, the survival and success rate of 1243 patients from 1654 premolars with developing or fully developed roots transplanted to the posterior region were calculated for different age groups.

This is the first paper that reports on such a large number of transplanted premolars. Because of the large sample size, it was possible to divide the data based on the patient's age in three groups:

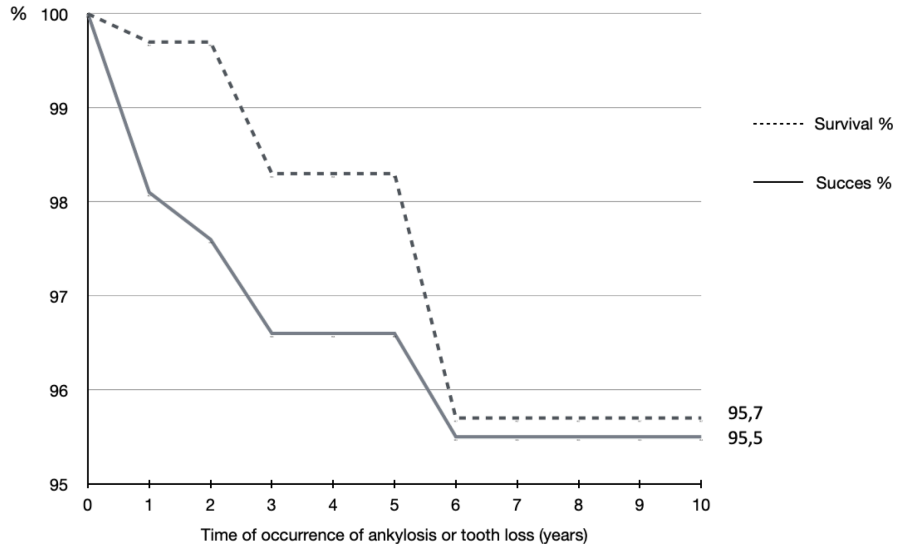


FIGURE 3 Kaplan–Meier survival and success analysis for mature tooth transplants <18 years.

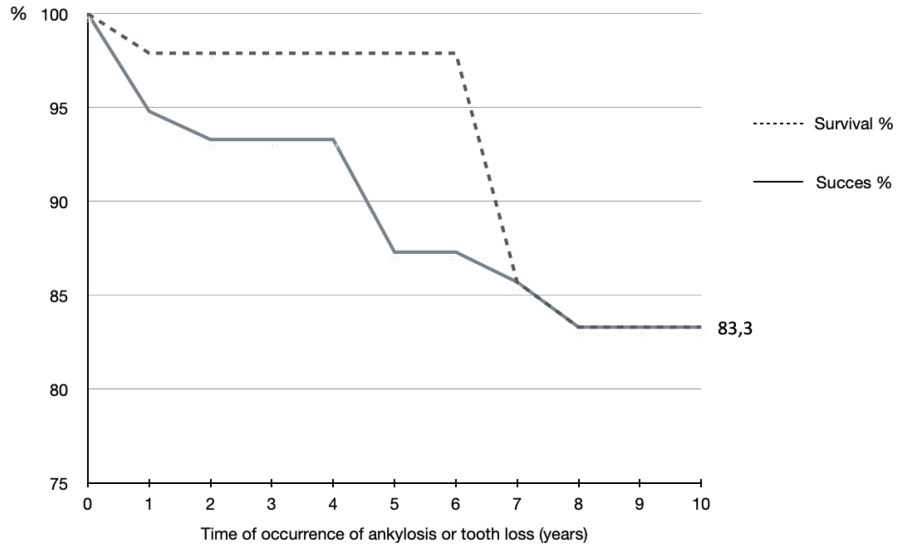


FIGURE 4 Kaplan–Meier survival and success analysis for mature tooth transplants ≥18 years.

premolars with developing roots (IMRD group), fully developed premolars that were transplanted in adolescents (MRD <18-year group) and fully developed premolars transplanted in adults (MRD ≥18-year group).

The definition of a successful tooth replacement in young and adolescent patients may differ from that in an adult. The optimal end point of treatment in an adult is to have a successful transplant that remains in situ for many years. However, in growing patients with missing teeth or compromised teeth for instance due to traumatic injuries, continued induction of alveolar bone growth is most important. Therefore, in a growing patient a successful transplant may be defined not only as a 'biological space maintainer' but also an optimal tooth replacement. Even if an autotransplant survives the majority of the skeletal adaptation and facial growth, it can still be considered successful. Such a tooth replacement achieves the functional, biological and aesthetic goals for that particular period. The most important parameter for autotransplantation in growing patients is the absence of ankylosis. Therefore, this factor can serve as a primary measure of success in this group of patients. This measure of success might contrast with that in an adult patient. Skeletal adaptation and facial growth is limited and, therefore, an ankylosed tooth is less significant.[25]

Several studies have reported a wide range of success and survival rates, ranging from 1 to 41 years of follow-up. Objective evaluation of the success rates of autotransplantation is challenging in published studies owing to a large variance in parameters evaluated. These parameters included the retrospective study design and inconsistencies in the time of follow-up; number of transplanted teeth size; differences in operator skills; and variation in pre-operative, surgical and post-operative parameters.[26] This inconsistency in published outcomes is further confounded by studies, including different types of donor teeth in their samples. For example, consider a heterogeneous sample which includes third molars and impacted canines in the same group as the premolars. This most probably dilutes the success rate of the premolars and does not provide a reliable percentage of success.[27]

Disturbed periodontal healing is associated with surgical trauma and delayed or insufficient orthodontic loading after transplantation. We have observed that all cases associated with surgical trauma were cases where the surgical procedure was recorded as 'difficult' either due to the anatomy of the donor tooth or the recipient site. We have also observed that most of the cases with unfavourable periodontal healing were cases that were done in the beginning of the observation period, as the surgical technique was refined over a period of time. This is consistent with previous studies showing the importance of experienced surgeons for successful outcomes after transplantation.[11,13,14] However, some studies have shown no significant differences in terms of operator experience and occurrence of adverse effects.[28,29] The authors noted that as with all dental procedures, experience was required.[29] The use and manufacturing of a replica of the donor tooth based on a previous CBCT, can facilitate the autotransplantation process by reducing the manipulation and the time out of the alveolus of the donor tooth, especially in the case of less experienced operators.[30,31]

In addition, since 2017, fully developed donor teeth (Moorrees Stages 6 and 7 root development) were preloaded with an orthodontic appliance on average 2–4 weeks prior to transplantation. Through this additional loading with an extrusive force, an increase in the cell proliferation of the periodontal ligament can be induced to promote healing at the receptor site. Moreover, due to preloading the extraction is easier with a lower chance of damage to the coronal part of the donor tooth. Both outcomes can be beneficial for the success of tooth transplantation.[32]

Delayed orthodontic loading or insufficient orthodontic force can also result in ankylosis, especially in teeth with fully developed roots (Moorrees' Stages 6 and 7 root development). Orthodontic loading time influences periodontal healing and root resorption as observed in beagle dogs.[33,34] The teeth of these dogs were extracted and autotransplanted. Different time points were selected to orthodontically load half of the transplanted teeth using different time courses. Changes in the periodontium were evaluated by measuring the probing pocket depth, histomorphometry and expression of alkaline phosphatase and basic fibroblast growth factor. In general, orthodontically loaded teeth showed a lower incidence of ankylosis than the unloaded teeth. Autotransplanted teeth loaded by orthodontic treatment 4 weeks after surgery for a 2-week duration had the best performance.[34] We also observed that orthodontic preloading of the fully developed teeth, as well as orthodontic loading with sufficient forces 3–4 weeks after transplantation, reduced the incidence of ankylosis and replacement root resorption.

4.1 | Immature premolars

In teeth with open apices, it is challenging to achieve periodontal and pulpal healing at the recipient site. Considering this, Moorrees' Stage 2/3 to 3/4 of the root of the donor tooth is optimal for transplantation, that is, Moorrees' Stage 4 to beginning of Stage 5 of root development. When transplanting premolars with the intention of revascularisation of the pulp, the age span is limited to approximately 9–12 years of age.[11] The average age of the IMRD group was 12.7 years, indicating that the patients were referred late. As a consequence, 49.1% of the premolars were transplanted at Moorrees' Stages end 5 to 6 of root development. At this stage of root development, there is an increased risk of impaired endodontic healing. However, when antibiotic prophylaxis was prescribed 1 h before transplantation, as described by Andreasen et al.,[11] the percentage of complications in endodontic healing was reduced to a level similar to that in the case of donor teeth with Moorrees' Stages 4 to beginning Stage 5 of root development. This finding indicates that patients who are older and, therefore, at a more suitable age to undergo this type of surgery, can be successfully treated.

Few comparative studies on the transplantation of premolars with an open apex to the posterior region are available. In 1996, Lundberg and Isakson[35] reported it to be a reliable method with good prognosis in cases of agenesis of the posterior teeth and the availability of a suitable donor tooth. In 2010, Mensink and Merkesteyn[36] reported that 63 premolars were transplanted solely into the premolar region. The survival was 100% after 1 year, whereas in 12%, a high percussion sound was observed, which is indicative of impaired periodontal healing with ankylosis. Moreover, in 5% of the premolars an endodontic treatment was needed due to periapical resorption. After an average 4.8 years follow-up period Kvint et al., in their work in 2010,[26] reported a loss in six of the 52 premolars with an open apex that were transplanted to the posterior zone. In 1974, Slagsvold & Bjercke[10] reported 34 transplanted partially formed premolars over a period of 6.2 (range, 3.3–13.8) years. They transplanted seven first premolars (five upper and two lower) and 27 s premolars (13 upper and 12 lower) to replace the missing premolars in the upper and lower jaws. None of the premolars were lost during the evaluation period. In the present retrospective analysis, 929 premolars with an open apex were transplanted to the posterior region and followed-up over a period of 10 years, with a cumulative survival rate of 93.3%. Only three teeth were lost because of impaired periodontal healing.

4.2 | Mature premolars

In the case of premolars with fully developed roots, endodontic treatment was performed, preferably and if possible, before the transplantation procedure. The rationale for this workflow is that the success of an endodontic treatment of a tooth with a vital pulp is higher (92%–95%) compared to that of a necrotic pulp (72%–86%).[37]

Limited reports are available in the literature regarding the transplantation of fully developed premolars (MRD group). A systematic review published in 2004 reported a survival rate of 92.3% after 5 years.[38] Kokai et al., in their work in 2015,[39] evaluated 54 fully developed premolars, 13 of which were transplanted to the anterior region and 41 to the posterior region. Fifteen premolars were

transplanted in patients aged <18 years, while 85 transplantation were performed in patients aged ≥18 years. Based on overall data, the authors reported a cumulative survival rate of 89.5% after 10 years. In the present retrospective analysis, the cumulative survival rate of premolars transplanted into the posterior region reported for the adolescents (MRD <18 years) was 95.7% after 10 years, which was higher than the survival rate reported in both the aforementioned studies. The time of endodontic treatment (if possible, before transplantation), time of orthodontic loading (3–6 weeks postoperatively), and the large number of included premolars may be possible explanations for the higher survival rate observed in the present retrospective analysis. In the older group (MRD ≥18 years) the survival rate was lower (83.3% after 10 years). Differences in periodontal parameters and healing potential between adolescents and adults may account for the lower survival rates observed in this group.

4.3 | Limitations

One of the limitations of this retrospective analysis was the small number of participants who attended follow-up visits after 3 years. The travel costs and time were the most important reasons for this, as the population consisted of patients from across the country. In addition, after the completion of orthodontic treatment and without experiencing any complaints or discomfort, a number of patients (and their parents/guardians) were unfortunately unwilling to visit our clinic for a control visit.

5 | CONCLUSION

Transplantation of premolars with developing and fully developed roots is a predictable treatment modality with the potential to provide significant advantages from a cost–benefit perspective if a strict treatment protocol is followed to preserve the intact periodontal ligament around the donor tooth, which is a key factor for success. Regular follow-up visits are necessary for timely diagnosis and management of complications that may jeopardise the survival and success of the transplanted tooth. Future research is needed to optimise the guidelines to further minimise the occurrence of complications and possible loss of transplanted premolars.

AUTHOR CONTRIBUTIONS

Manfred Leunisse, Edwin Eggink and Dick Barendregt conceived the idea. Anna Louropoulou, Marcel Linssen and Dick Barendregt collected the data. Dick Barendregt, Jens Ove Andreasen and Wim Coucke analysed the data. Anna Louropoulou, Fridus van der Weijden and Dick Barendregt contributed to the writing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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