FEATURE ARTICLE

OUTCOMES OF AUTOTRANSPLANTED THIRD MOLARS WITH COMPLETE ROOT FORMATION: A SYSTEMIC REVIEW AND META-ANALYSIS

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ABSTRACT

Objectives

Clear evidence is lacking regarding the outcomes of autogenous tooth transplantation (ATT) of third molars with complete root formation. The current review aims to explore the long-term survival and complication rates.

Methods

A comprehensive search was performed in December 2022 of the PubMed, Scopus, Embase, EBSCO, Ovid, Science Direct, and Web of Science databases. The systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines and registered at the International Prospective Register of Systematic Reviews (CRD42022337659). The pooled survival, root resorption, and ankyloses rates were calculated. Subgroup analyses were performed to explore the effects of sample size and 3D techniques.

Results

Twelve studies from 5 countries fulfilled the eligibility, with 759 third molars transplanted in 723 patients. Five studies reported 100% survival at 1-year follow-up. After excluding these 5 studies, the pooled survival rate was 93.62% at 1 year. The survival rate of 1 large sample study was significantly higher than that of small ones at 5 years. The complications of studies using 3D techniques were: root resorption 2.06% (95% CI: 0.22, 7.50) and ankyloses 2.81% (95% CI: 0.16, 12.22), compared to those without 3D techniques: root resorption 10.18% (95% CI: 4.50, 17.80) and ankyloses 6.49% (95% CI: 3.45, 10.96).

Conclusions

ATT of third molars with complete root formation is a reliable alternative for replacement of a missing tooth and has a promising survival rate. The use of 3D techniques can reduce complication rates and improve long-term survival.

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KEYWORDS

Autogenous tooth transplantation, Third molar, Complete root formation, Closed apex, Survival rate

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INTRODUCTION

Autogenous tooth transplantation (ATT), a therapeutic strategy to replace a non-restorable or missing tooth with restricted indications, was first reported in 1950.[1] It is defined as the surgical movement of an embedded or erupted donor tooth to a recipient site in the same individual, essentially a controlled extraction and reimplantation in an extraction site or surgically prepared socket.[2-5] Viable but malpositioned teeth—including third molars, premolars, canines, and supernumerary teeth—can be used as donor teeth. Successful ATT restores the vital periodontium, proprioception, and alveolar bone volume. It also preserves orthodontic movement and functional adaptation and potentially has favorable aesthetics.[6,7] Thus, the patient can have a natural chew and biological response. Yet because of the unclear long-term survival outcomes, surgeons and patients are hesitant to accept ATT.[8, 9] In the era of implant-driven dentistry, the advent of titanium implant rehabilitation has reduced the use of ATT treatment in routine clinical practice.[3]

Recent advances in diagnostic and surgical techniques have increased the success rate of ATT.[10, 11] ATT is superior to the use of a fixed or removable prosthesis to replace a missing or hopeless tooth and may not require the preparation of adjacent teeth. It is also more cost-effective than conventional prostheses or dental implants. In addition, ATT can be performed at an early age and can provide orthodontic movement; therefore, it is more acceptable for most patients.[12-14] Nevertheless, poor prediction of outcomes hinders more widespread use of ATT.[9]

Several factors influence the outcomes of ATT, including factors related to the patient (sex, age), donor tooth (type, morphology, position, root development), recipient site (location, local inflammation, alveolar bone volume and quality), and procedure (stabilization method and duration, antibiotic use, autograft or osteotomy, storage, orthodontic interventions).[14, 15] Although the reported success and survival rates vary, ATT using an immature tooth has a favorable prognosis. Therefore, it is more commonly used in pediatric patients, in whom dental implants are contraindicated.[14] Nevertheless, in a systemic review of ATT with complete root formation of all types of teeth, 1- and 5-year survival rates were 98% and 90.5%, respectively.[16] This supports the hypothesis that ATT with mature teeth has adequate clinical outcomes.

The increasing demand for high-level evidence of the effectiveness of oral healthcare interventions has led to a marked increase in systematic reviews.[17] To the best of our knowledge, ATT using third molars with complete root formation is poorly documented, and a systematic review is lacking. To provide evidence-based guidelines for clinicians, we thus explored the long-term survival and complication rates, and the prognostic factors of ATT using third molars with complete root formation.

MATERIAL AND METHODS

Protocol and Registration

A literature search, study selection, data extraction, and reporting of the results were conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[18] The systematic review protocol was registered with the International Prospective Register of Systematic Reviews (no. CRD42022337659). The protocol was designed to answer the following questions: What are the long-term survival and complication rates of ATT using third molars with complete root formation? The following PICOS criteria were applied:

Population: Patients Who Underwent Att Treatment

Intervention: ATT using third molars with complete root formation.

Comparison: None (not applicable for an outcome analysis review).

Outcomes: Survival rate and complication rate.

Literature Search Strategy

A comprehensive electronic search was performed in December 2022 of the PubMed, Scopus, Embase, EBSCO (Dentistry & Oral Sciences Source, MEDLINE), OVID (Ovid MEDLINE ALL), Science Direct, and Web of Science databases. The following structured terms were searched in abstracts, as well as titles or keywords: (third molar OR wisdom tooth OR wisdom teeth) AND (autotransplantation OR transplantation) AND (complete root formation OR mature OR closed apex). In addition, we conducted a manual search by checking the reference lists and related articles in PubMed of the included articles. Search strategies were developed with the assistance of an experienced librarian.

Eligibility Criteria

The inclusion criteria were (1) primary human studies, including prospective and retrospective research on third molar ATT with complete root formation; (2) studies that reported at least one of the survival, success, root resorption, or ankyloses rates; (3) studies with a minimum follow-up of 1 year; and (4) studies published in English.

The exclusion criteria were (1) studies that did not report the success or survival rate of ATT of third molars; (2) studies that investigated ATT using donor teeth with incomplete root formation; (3) studies that included ATT with teeth other than third molars or with a mixture of other types of teeth; (4) case reports, case series, expert opinions, and review articles; (5) animal or in vitro studies; and (6) studies published in languages other than English.

Study Selection and Data Extraction

Study screening and selection were performed independently by 2 authors (JH and HX), and studies that did not meet the inclusion criteria were discarded. When a decision could not be reached based on the title and abstract, or in cases of disagreement, a discussion with a third reviewer was held until mutual agreement was reached. The articles were imported into EndNote X9, and duplicate files were excluded. Two reviewers (JH and YG) independently screened the full texts to identify potentially eligible studies. A checklist was used to extract from eligible articles the first author, publication year, country, participant characteristics, donor tooth, recipient site, splinting procedure and duration, success rate, survival rate, root resorption rate, ankyloses rate, and timing of endodontic treatment. The extracted information was cross-checked to verify its integrity.

Statistical Analysis

Based on the recommendations in the Cochrane Handbook for Systematic Reviews of Interventions, the ROBINS-I (Risk of Bias in Non-Randomized Studies of Interventions) tool was used to assess the risk of bias in the included studies.[19] Two reviewers (YG and DL) independently assessed each article for bias due to confounding, in the selection of participants, in the classification of interventions, due to deviations from intended interventions, due to missing data, in the measurement of outcomes, and in the selection of the reported result. Each study was assigned a rating of low risk, moderate risk, serious risk, or critical risk.

The fixed- or random-effects restricted with maximum-likelihood models were performed based on heterogeneity to calculate the pooled failure, root resorption, and ankyloses rates, and then the survival curves were generated using the Freeman-Tukey transformation. Forest plots were used to describe the rates and corresponding 95% confidence intervals (CIs) for each study and overall estimate. Heterogeneity was analyzed by chi-square test with N–1 degrees of freedom, the significance level was set at 0.10. In the absence of heterogeneity ($P \geq .10$), a fixed effect model was applied. However, when $P < .10$, which indicated the existence of heterogeneity in the studies, a random effect model would be used for the meta-analysis. The quantitative statistic I^2 was used to assess the magnitude of heterogeneity.[19]

In cases of missing data, we contacted the corresponding authors for supplemental materials or clarification. If no response was received, the missing data were treated according to the recommendations in the Cochrane Handbook for Systematic Reviews of Interventions.[19] Because clinical data could not be obtained from patients lost to follow-up, only teeth with a specific outcome were included in the quantitative analysis.

A subgroup analysis was performed to explore the effects of sample size on the pooled survival rate, and a survival curve was generated. Another subgroup analysis evaluated the effects of 3D techniques on the failure, root resorption, and ankyloses rates. A funnel plot was generated to visually assess the publication bias, and Egger's test, as well as Begg's test, were also conducted at a significance level of 0.10. Analyses were performed in R software (version 4.2.0) with meta package (version 5.2–0) and Origin software (version 9.1). $P < .05$ was considered as statistical significance.

RESULTS

Study Selection

The electronic searches yielded 176 articles. After we discarded 118 duplicates, 58 articles were screened based on the titles and abstracts, which resulted in 24 articles for full-text assessment. One article was not retrievable even with the assistance of an experienced librarian, and 1 was retracted. Subsequently, 13 potentially relevant studies were excluded, leaving 9 studies. A manual search of related articles in PubMed yielded 3 studies. Therefore, 12 studies met the inclusion criteria and were subjected to qualitative and quantitative analysis. A flowchart of the literature selection is shown in Figure 1. Several studies were excluded because they involved both mature and immature third molars[20-22] or a combination of molars, premolars, and canines.[15,23-25] Yoshino *et al*. published 2 articles on the same cohort of autotransplanted teeth,[26, 27] one of which investigated the outcomes of male patients.[26] The other, which included both male and female patients, was selected for further analysis.[27]

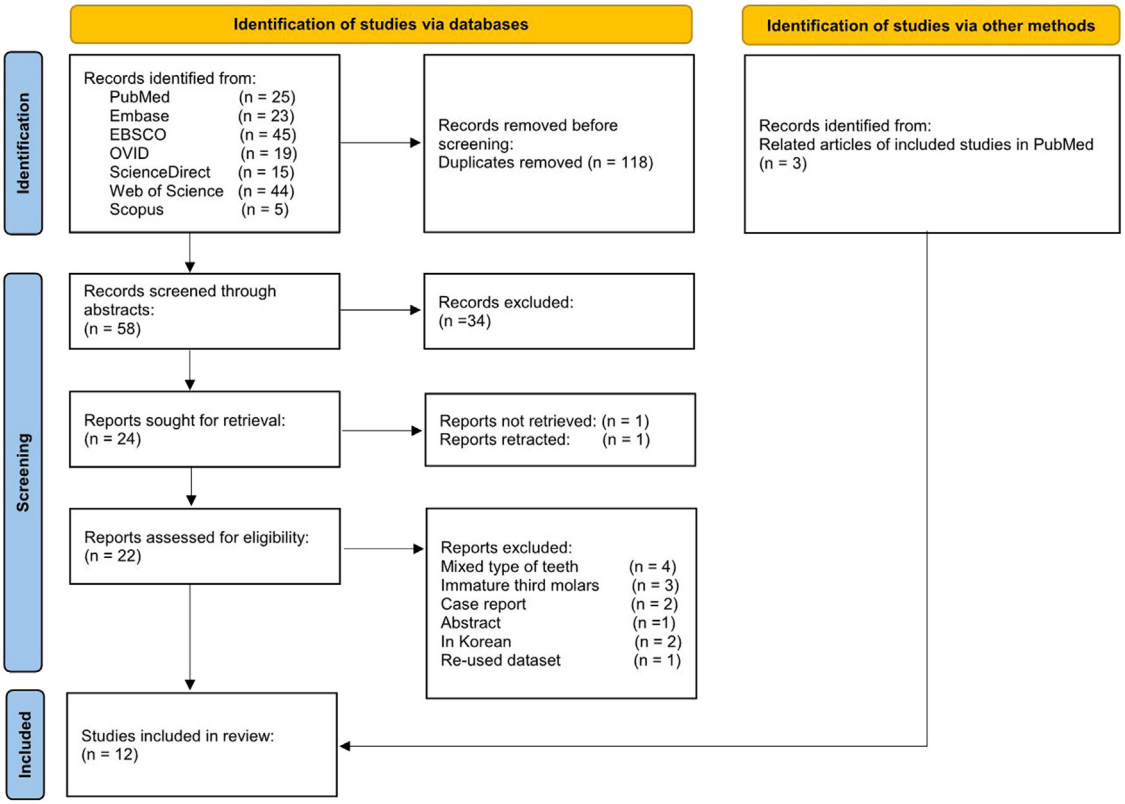
Characteristics of Included Studies

The 12 included studies were published between 1998 and 2022. Six studies were conducted in China, 2 in Japan, 2 in India, 1 in Italy, and 1 in Sweden. Controlled studies were absent; 6 of the cohorts were retrospective, and 6 were prospective. Sample sizes ranged from 8 to 360 patients, with a mean of 60.3 patients. A total of 723 patients were enrolled, and 759 third molars with complete root formation were transplanted (Table 1).

Risk of Bias

As assessed with the ROBINS-I tool, all studies presented a low risk of bias for the classification of interventions, deviations from intended interventions, the measurement of outcomes, and selection of the reported result. One study had a moderate risk in terms of the selection of participants,[28] and another had a moderate risk for missing data.[29] Regarding confounding bias, 8 of the 12 studies had a critical risk of bias, 2 a serious risk,[30,31] and 2 a low risk[32,33] (Figure 2).

Figure 1. PRISMA flowchart of the literature search, screening, and selection.



Survival rate

The follow-up period varied considerably among the included studies. Three studies had a follow-up period of 10 years,[27,28,34] one of 5 years,[31] one of 4 years,[8] four of 2 years,[29,33,35,36] and three of 1 year.[30,32,37] Five studies achieved a 100% survival rate after 1 year.[8,29,33,35,37] The pooled survival rate at 10 years of the 12 included studies is shown in Figure 3 . The overall survival rate might have increased because of the inclusion of the 5 studies with a 100% survival rate. When we excluded these 5 studies, the pooled survival rate was 93.62% at 1 year. There was a significant difference in the overall survival rate between all the 12 included studies and the residual 7 studies after excluding the 5 studies with a 100% survival rate ($P < .001$), which suggested that the true level of survival rate might be lower than the pooled rate of the 12 included studies.

A sensitivity analysis showed a significant difference ($P = .018$) in the pooled survival rate between the studies with a low risk of bias and all included studies, which indicated that the pooled survival rate was influenced by the study quality. Ideally, only studies with a low risk of bias should have been included in the statistical analysis. However, 10 of the 12 studies had a serious or critical risk of bias; therefore, the results should be interpreted with caution. After we excluded the 2 low-risk studies, the pooled survival rate did not differ from that of all included studies (1 year, 98.98% vs 97.77%, $P = .248$). This review included 1 large sample study of 388 ATT third molars;[27] the other studies were small samples. Only 1 of the 11 small sample studies reported the annual survival rate after 6 years.[28] Therefore, we pooled the cumulative survival rate for the first 5 years (Figure 4). The pooled survival rate of the large sample study was significantly ($p = .023$) higher than that of the small sample studies (91.30% vs 81.51%) at 5 years. Therefore, the large sample study had a dominant effect on the pooled outcome.

Pooled Failure, Root Resorption, and Ankyloses Rates With and Without 3D Techniques

Various factors can lead to the failure of ATT with third molars, such as periodontal attachment loss, root resorption, and ankyloses. Most studies reported rates of root resorption[27-35] and ankyloses,[8,31-35] which constituted the majority of failed cases. The pooled failure rate was 8.99% (95% CI:

Table 1. Summary of descriptive characteristics of 12 included articles.

First author	Year	Country	Study design	Patients-(M/F)-Teeth	Age (y)	Donor site -> Recipient site	Extra-oral time	Endodontic treatment timing	Splinting material	Splinting duration	3D techniques	Follow-up duration	Success rate (%)	Survival rate (%)	Root resorption rate (%)	Ankyloses rate (%)
Dhar[30]	2022	India	prospective	20-(NR/NR)—20	NR	Man 3rd -> Man molar: 20	NR	NR	NR	NR	acrylic replica	1 y	85%	90%	10%	5%
Marcello[31]	2022	Italy	retrospective	60-(23/37)—61	45.58 (17-76)	Man 3rd -> Man molar: 46 Max 3rd -> Max molar: 15	<15 min: 56	<4w	twisted wires 53 cross-coronal sutures 8	<4w	NR	5.42y	93.4%	93.4%	<6.6%	4.9%
Keranmu[29]	2021	China	prospective	52-(22/29)—52 CGF 26: (1 lost) Control 26	32.63 (22-46)	Max 3rd -> Man molar: 19 Man 3rd -> Man molar: 33	41.8 s (30-60)	when mobility less than or equal to grade I	good initial stability, "8" suture for 1 w; poor initial stability, fiber-glass band for 4 w	1-4 w	tooth replicas	26 m (18-36)	CGF 100% Control 92.3%	96.1%	none	none
Xu[36]	2021	China	retrospective	11-(4/7)—11	34.9 ± 7.5	Max 3rd 8 + Man 3rd 3 -> anterior 2 + premolar 6 + molar 3	NR	2 w - 3m	8 anterior & premolars, buccal or lingual elastic fixation; 3 molars, both buccal and lingual elastic fixation	NR	none	24.8 ± 16.4 m	90.91%	100%	none	none
Xia[33]	2020	China	prospective	27-(7/20)—28	27.6 (20-34)	Max 3rd -> Max molar: 5 Max 3rd -> Man molar: 6 Man 3rd-> Max molar: 7 Man 3rd-> Man molar: 10	2.5 m (1-5)	1-2 w	over-crown suture or composite splint	1-2 w	tooth replica	2 y	100%	100%	none	none
Wu[35]	2019	China	retrospective	10-(8/2)—10	31.6 (19-42)	Max 3rd -> Man molar: 1 Man 3rd -> Max molar: 3 Man 3rd -> Man molar: 6	1.35 m (0-4)	2 w	splint with a multi-layer fiber-glass band	5 w	tooth replica, 8 cases with GBR	24 m	100%	100%	none	none

(*continued on next page*)

Table 1 (*continued*)

First author	Year	Country	Study design	Patients-(M/F)-Teeth	Age (y)	Donor site -> Recipient site	Extra-oral time	Endodontic treatment timing	Splinting material	Splinting duration	3D techniques	Follow-up duration	Success rate (%)	Survival rate (%)	Root resorption rate (%)	Ankyloses rate (%)
Shinde[32]	2018	India	prospective	42-(15/27)—42	36 (22-50)	NR	NR	1 m	suture, wire for mobile tooth,	1 w	NR	1y	78%	78%	19%	2%
He[8]	2018	China	prospective	8-(4/4)—8	26.88 ± 2.64	Max 3rd -> Max molar: 2 Max 3rd -> Man molar: 2 Man 3rd -> Man molar: 4	6 immediate, 2 < 3 min	2 w	0.25 mm-diameter steel wires	usually 4 w	replicas with local splints, surgical templates, arch bars	2.00 ± 1.06 y (1-4)	87.5%	87.5%	none	12.5%
Yu[34]	2017	China	retrospective	60-(28/32)—65	33.1 (19-55)	Max 3rd ->Max premolar:2 Max 3rd->Man premolar:4 Max 3rd -> Max molar: 11 Max 3rd -> Man molar:9 Man 3rd->Max premolar:3 Man 3rd->Man premolar:3 Man 3rd -> Max molar: 5 Man 3rd -> Man molar:28	15 m	>20 y, RCT; < 20 y, RCT if vitality test negative	non-absorbable surgical sutures	2-3 w	none	9.9 y (7-13)	NR	90.8%	10.8%	9.2%
Yoshino[27]	2014	Japan	retrospective	360-(171/189)—388	male: 44.8 (20-72) female: 42.0 (20-74)	Max 3rd -> Max incisor: 1 Max 3rd ->Max premolar:7 Max 3rd->Man premolar:5 Max 3rd -> Max molar: 67 Max 3rd -> Man molar:114 Man3rd -> Max incisor: 1 Man 3rd->Max premolar:1 Man 3rd->Man premolar:2 Man 3rd -> Max molar: 44 Man 3rd-> Man molar:146	NR	2-4 w, or more	surgical sutures, wire splint or both	sutures 1 w, splint 2-4 w, or more	NR	0-10 y	NR	male: 5-Y 86.0% 10-Y 59.1% female: 5-Y 92.6% 10-Y 81.9%	NR	NR

(*continued on next page*)

Table 1 (*continued*)

First author	Year	Country	Study design	Patients-(M/F)-Teeth	Age (y)	Donor site -> Recipient site	Extra-oral time	Endodontic treatment timing	Splinting material	Splinting duration	3D techniques	Follow-up duration	Success rate (%)	Survival rate (%)	Root resorption rate (%)	Ankyloses rate (%)
Mejàre[28]	2004	Sweden	prospective	50-(NR)—49 (1 lost)	36.7 (21-66)	Max 3rd -> Max molar: 12 Max 3rd -> Man molar: 7 Max 3rd ->Max premolar:1 Man 3rd -> Max molar: 4 Man 3rd -> Man molar: 24 Man 3rd->Man premolar:1	NR	3-4 w	most cases 2 interdental sutures; 10 cases, a string	10 d	none	NR	NR	81.4%	6.1%	NR
Akiyama[37]	1998	Japan	retrospective	23-(NR) —25	29.6 (20-54)	NR -> Max molar: 10 NR -> Man molar: 15	NR	2-3 w	silk sutures 2, adhesive resin 10, light polymerizing resin 7, temporary polymerizing bridge 2, circumferential wiring 3, wire splint 1	30.4 d (7-42)	None	6-18 m	100%	100%	none	none

NR, not reported; CGF, concentrated growth factor; Max, maxilla; Man, mandible; GBR, guided bone regeneration; RCT, root canal therapy; 5-Y, 5 years.

Figure 2. Risk of bias for the included studies.

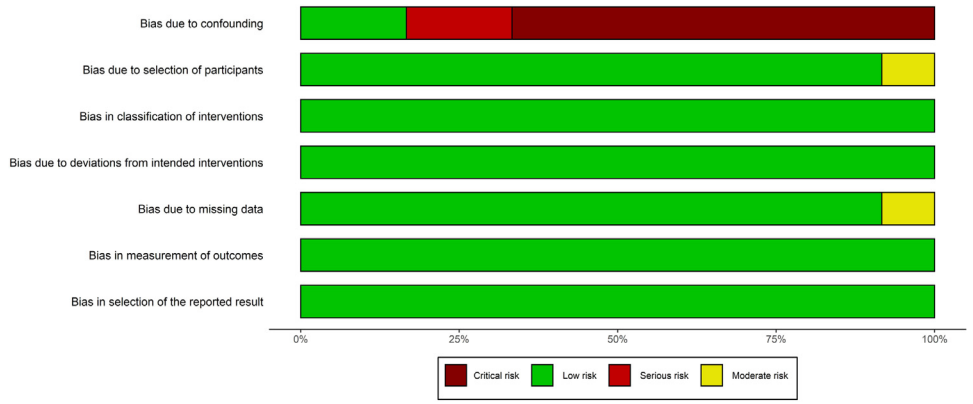


Figure 3. Pooled survival rate at 10 years of the 12 included studies.

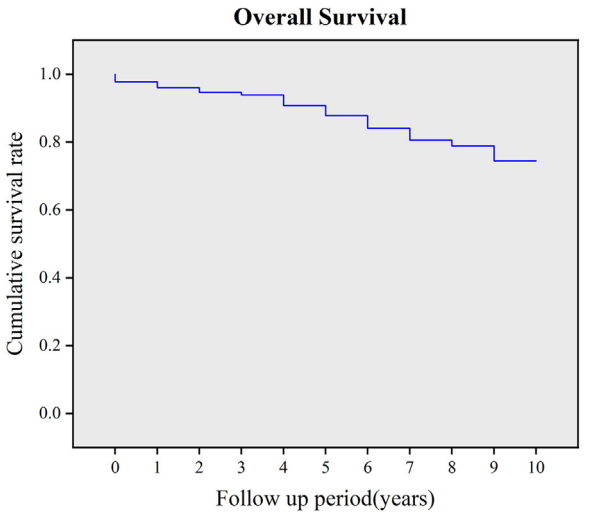
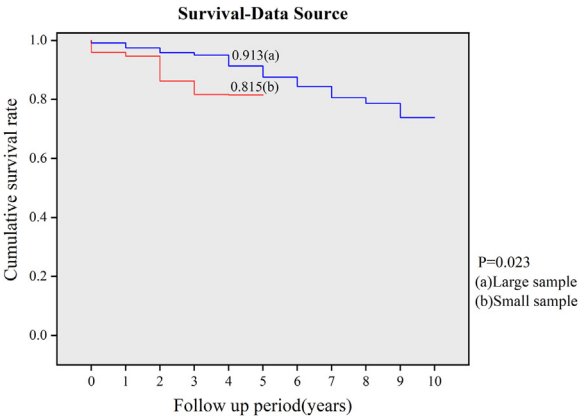


Figure 4. Survival analysis of large and small sample studies.



5.54, 13.17), and there was significant heterogeneity across studies ($I^2 = 56.41\%$, $P = .008$; Figure 5).

Four of the 12 studies reported the use of 3D techniques (computer-aided rapid prototyping tooth replicas and 3D-printed guiding templates) for ATT in 96 patients (12.66%), which significantly influenced the outcomes.[8,29,33,35] With 3D techniques, the pooled failure rate was 3.76% (95% CI: 0.98, 9.60) based on a fixed-effects model, and heterogeneity was low ($I^2 = 2.39\%$, $P = .380$). Without 3D techniques, the pooled failure rate was 11.30% (95% CI: 7.49, 15.77) based on a random-effects model, and there was significant heterogeneity across studies ($I^2 = 46.37\%$, $P = .071$; Figure 5).

The pooled root resorption rate was 6.96% (95% CI: 3.33, 11.80) in 11 included studies (Figure 6), while 1 study was excluded due to missing data.[31] The pooled ankyloses rate was 5.64% (95% CI: 3.08, 9.36) in all the 12 included studies (Figure 7). For the studies that used 3D techniques, the pooled rates were 2.06% (95% CI: 0.22, 7.50) for root resorption and 2.81% (95% CI: 0.16, 12.22) for ankyloses. For the studies that did not use 3D techniques, the pooled rates were 10.18% (95% CI: 4.50, 17.80) for root resorption and 6.49% (95% CI: 3.45, 10.96) for ankyloses. Therefore, the

Figure 5. Forest plot of the pooled failure rate with and without 3D techniques.

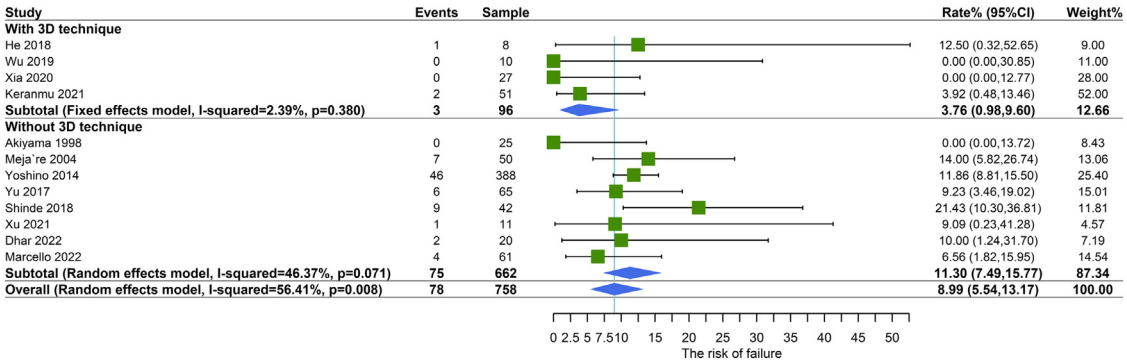


Figure 6. Forest plot of the pooled root resorption rate with and without 3D techniques.

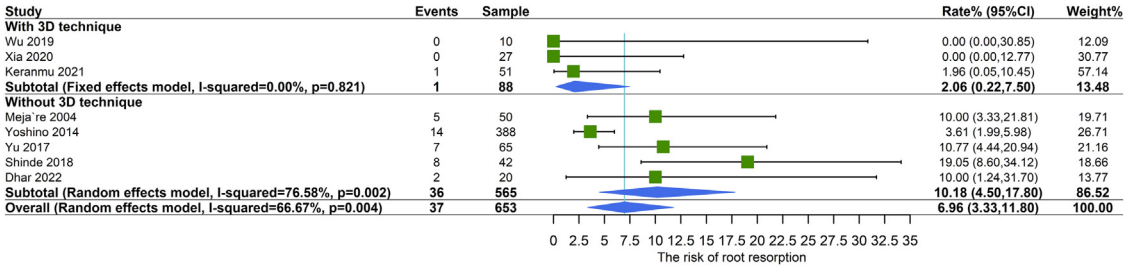
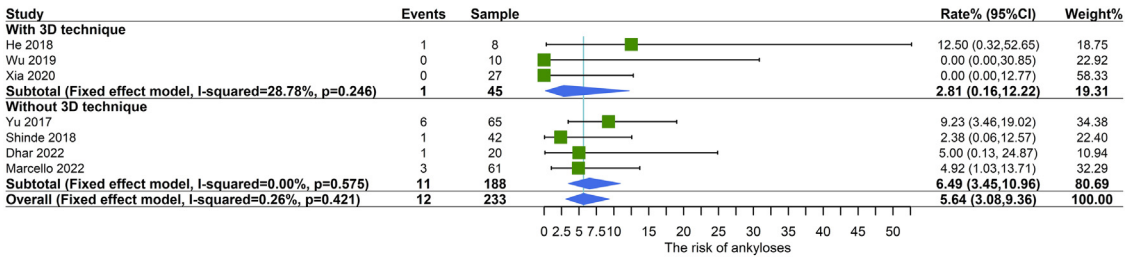


Figure 7. Forest plot of the pooled ankyloses rate with and without 3D techniques.



3D techniques might have reduced the root resorption and ankyloses rates.

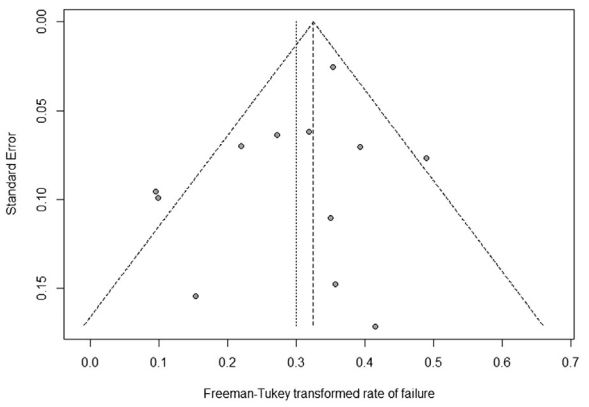
Publication Bias

Three out of 12 included studies reported a failure rate of zero,[33,35,37] thus the Freeman-Tukey transformation method was used to transform the rate of failure (Figure 8). No publication bias were found (Egger's test: $P = .268$; Begg's rank test: $P = .681$). However, the funnel plot showed that 3 studies presented heterogeneity,[32,33,37] including 2 studies that with a low risk of bias.[32,33]

DISCUSSION

ATT is a valid treatment strategy for tooth replacement, being more economical, biological, and esthetic than prosthetic rehabilitation.[38] The indications for ATT include im-

Figure 8. Funnel plot of publication bias.



pacted or ectopic teeth, premature and/or traumatic tooth loss, loss of teeth because of tumors or on iatrogenic grounds, congenitally missing teeth in one arch in combination with a discrepancy in arch length or clinical signs of tooth crowding on the opposing arch, replacement of teeth with a bad prognosis, and/or developmental dental anomalies.[39] ATT with immature root formation has a higher success rate and so is preferable for use in pediatric patients.[39-42] It's reported that ATT of third molars with complete root formation has a lower survival rate than that of third molars with incomplete root formation.[40] However, third molars with complete root formation are more common in adult patients and can serve as donor teeth. According to the outcomes of this review, the technique of ATT using mature third molars seems more popular in Asian countries with a larger population, including China, Japan, and India. The possible explanation might be due to: cultural differences, the Asians exhibit a greater desire of preserving natural teeth than westerners, especially in China; racial differences, the harvesting of a mature third molar without damaging the roots seems more feasible in Asians because of their relatively simpler root anatomy and lower bone density; cost differences, the significantly lower cost of ATT compared to implants or conventional prosthetics would lead the patients to choose the ATT technique when within the indications.

Prognostic Factors

Several factors are reportedly associated with the outcomes of ATT. These include patient age, sex, tobacco smoking, plaque control, periodontal condition, root anatomy, preservation of the periodontal ligament (PDL), surgical trauma, history of endodontic treatment, surgeon skill and experience, extra-alveolar time, recipient site integrity (local inflammation, alveolar bone volume and quality), adjacent bone defect, stabilization method and duration, and the timing and quality of endodontic treatment.[20,21,25,35,39]

A better prognosis was expected for younger patients who underwent ATT. This is because the regenerative potential of PDL cells decreases with age and might interfere with the normal adaptation of the donor tooth to the recipient site.[43] Nevertheless, the survival rate of ATT with complete root formation is not influenced by the age of the patient.[24] The harvesting of mandibular donor teeth is more difficult than the harvesting of maxillary teeth because of their higher bone density. Therefore, detaching the donor tooth would likely be more traumatic. However, it is surprising that mandibular donor teeth had the same cumulative survival rate as maxillary donor teeth.[15]

Preserving the viability of PDL tissue is critical for successful ATT. Genetically speaking, PDL stem cells can differentiate into fibroblasts, cementoblasts, and osteoblasts.[7] Optimal healing depends on the number of these blast cells attached to the root surface; therefore, the donor tooth should be extracted as atraumatically as possible. Ideally, a donor third molar should be (1) reasonably strong, with good root volume and length; (2) readily extractable; and (3) periodontally healthy.[30] It is preferable to make an intra-crevicular incision before luxation to preserve as much PDL as possible.[5] Gauze should be placed over the crown before the extraction forceps are applied to prevent grazing of surface enamel or slippage onto the root surface.[44] Surgical extraction of the donor tooth is associated with a significantly higher incidence of root resorption.[45] After detachment, gentle manipulation of the donor tooth is required when it is transplanted to the recipient site. Along with mechanical damage, biochemical factors (pH, osmotic pressure, and dehydration) might also impact the viability of PDL cells.[7,45] Damaged PDL tissue might lose its natural resilience in the surrounding bone, leading to root resorption or ankyloses. Therefore, the extracted tooth should be stored in saline-soaked gauze, saline solution, or the donor site during preparation.[34,44] An extended extra-alveolar time of the donor tooth significantly affects the viability of PDL cells, leading to unfavorable root resorption. The European Society of Endodontology stated that the extra-alveolar manipulation of the donor tooth should not exceed 15 min.[44] An extra-alveolar time <15 min is associated with a significantly higher tooth survival rate.[45]

Numerous efforts have been made to minimize the extra-alveolar time of the donor tooth. Since extraction sockets require modifications to allow seating of the donor tooth, multiple attempts prolong the extra-alveolar time of PDL cells and ultimately lead to the failure of ATT.[8,35] The 3D approach not only allows the selection of the most suitable donor tooth according to tooth morphology but also shows the ideal 3D position and the required dimensions of the

alveolus during surgery. Computer-aided rapid prototyping tooth replicas and 3D-printed guiding templates were fabricated before surgery to improve the suitability of the donor tooth for the recipient site. This technique reduced the number of fitting attempts, thus minimizing the additional extra-alveolar time, improving the match between the donor tooth and the recipient site, and decreasing the required experience level of the surgeon.[3,5,35,44] 3D techniques improve the accuracy and stability of surgery and so are suitable for ATT.[8]

The recipient site should be free from acute infection and have substantial bone support.[46] To ensure that the donor tooth is not inserted with undue pressure, the recipient site should be slightly larger than the donor tooth.[5] A key factor for bone formation is the cervical approximation between the root surface of the transplanted tooth and the alveolar bone. The bone tissue below the cervical portion is a closed wound with little risk for infection and an increased tendency for adequate healing without complications. However, the condition of the recipient site varied significantly. According to the timing of tooth loss (ie a fresh or surgically prepared socket), different surgical techniques might be needed.[34] Implant drills with internal and external water cooling or piezoelectric inserts are recommended for this procedure.[3, 44]

Stabilization techniques for splinting teeth included the use of suture splints, surgical dressings, both suture splint and surgical dressing, wire–composite resin splint, composite resin splint, fiber-reinforced splint, and ligature wire.[3] Low initial stability is associated with a significantly lower incidence of ankyloses.[45] Wires are recommended in cases of insufficient stability. A flexible splint with a steel wire ≤0.3-0.4 mm in diameter provides physiologic tooth mobility, reducing the risk of ankyloses.[47] Appropriate functional movement during postoperative fixation is crucial for successful periodontal healing of the transplanted tooth; therefore, long-term rigid fixation is not recommended.

After transplantation, the occlusal interference must be adjusted to relieve occlusal and articulation forces.[3,5,44] A surgical dressing or periodontal packing is recommended to prevent infection and mechanical trauma of the transplant area during the first 2-3 days of wound healing. The long-term survival of ATT is influenced by occlusal status.[26] Therefore, it is advisable to check the occlusion periodically. According to tooth aesthetics and function, restorative treatment can be performed.[5] Finite element analysis (FEA) shows that the occlusal morphology improves the stress distribution in dentin and cortical bone, and possible fractures may be prevented with the new occlusal surface by crowning. The homogeneous stress distribution to the chewing forces is crucial in the long-term success of ATT.[48]

In ATT of third molars with complete root formation, the probability of pulp revascularization is negligible. Therefore, endodontic treatment is needed to prevent pulpal infection, consequent periradicular inflammation, and internal root resorption.[7,28] The timing of endodontic treatment was controversial and varied across studies. A retrospective study in Taiwan analyzed the relationship between endodontic treatment and survival rate in 1811 ATT third molars. Postoperative endodontic treatment resulted in a significantly lower extraction rate than preoperative or extraoral endodontic treatment during a mean follow-up of 8.33 years.[49] Because an increased extra-alveolar time results in damage to PDL tissue, extraoral endodontic treatment is not recommended.[5] Endodontic treatment should be initiated before surgery or 2 weeks after transplantation.[7,50] However, because access to mature third molars is limited, it is more feasible to perform endodontic therapy after surgery. The 2-week interval is crucial for the success of ATT. If endodontic treatment is performed too soon after surgery, additional damage to PDL tissue might result. However, the risk for root resorption was higher in studies that initiated endodontic treatment beyond 2 weeks because of infection in the root canal. A simplified approach to endodontic management involved extraoral apicoectomy and retrograde restoration after atraumatic extraction of the donor tooth. The patient was followed for 5 years, and radiography showed a regular root surface without evidence of periapical lesions or root resorption. Therefore, if appropriate sterility of the working field is maintained during surgery and a tight apical seal is achieved during extraoral treatment, orthograde endodontic treatment can be delayed or avoided.[51]

Success and Survival Rates

Success criteria were defined differently among the studies, and a standardized and internationally accepted consensus on success criteria is lacking. The success of ATT was evaluated based on clinical and radiographic parameters. The clinical parameters were (1) normal mobility, (2) normal percussion sound, (3) no periodontal pocket, (4) no sign of inflammation, (5) no discomfort, and (6) normal chewing. The radiographic parameters were (1) normal space of the periodontium, (2) no sign of progressive root absorption, and (3) a present lamina dura.[22,23,26,29,35] The following clinical and radiographic conditions were prerequisites for success: (1) normal function and physiologic mobility without pain or discomfort on palpation and percussion; (2) stable periodontal attachment apparatus (ie probing pocket depth ≤ 4 mm and clinical attachment level ≤ 5 mm); and (3) normal radiographic appearance of the PDL space around the transplanted tooth with no progressive root resorption, periapical radiolucency, or radiographic bone loss ≥ 50%.[21] However, the diverse criteria for success preclude a comparison of outcomes among studies.

Any signs and/or symptoms that severely impede the normal masticatory function of ATT, such as excessive mobility (horizontal movement > 2 mm or any vertical movement) be-

cause of periodontal bone loss, inflammation, root resorption, and persistent pain on mastication, were considered treatment failure.[45] Cases other than failure (ie tooth presence during follow-up) were defined as survival.[14] Because the survival rate was defined consistently across studies, the primary outcome of this systematic review was the pooled survival rate of ATT of third molars with complete root formation.

In a study of mature molar transplantation with a follow-up period of 11.9 ± 1.9 years, the success rate among the 21 analyzed cases was 80%, and the survival rate was 95%.[52] Studies using 3D techniques have reported higher success rates. By computer-aided rapid prototyping, a 100% success rate of 28 transplanted teeth was achieved.[33] In a retrospective series of 10 cases using 3D replicas, there was no sign of failure and a 100% success rate during the 1-year follow-up.[35] In this regard, 3D techniques minimize the trauma exerted on the PDL of the donor tooth by reducing the extra-alveolar time. Despite the low quality of the evidence, this approach results in higher and more homogeneous survival rates than conventional techniques.[21]

It is interesting that the medium-term survival rate in female patients was affected by operational risk factors, whereas the long-term survival rate in male patients was influenced by individual oral status.[27] The cumulative tooth success and survival rates of ATT with third molars were 91.7% and 97.2%, respectively, with a 2.5-year follow-up. These results were not influenced by recipient site integrity or root development.[21]

Complications

A lack of periodontal healing, root resorption, and ankyloses was frequently noted.[39,45] The main complications leading to failure were root resorption and ankyloses. Root resorption was defined as the ATT tooth exhibiting resorption signs on radiography.[14,45] Ankyloses was diagnosed when a metallic sound was detected on percussion test, disappearance of the PDL space and lamina dura, bone replacement of the root dentin, but no adjacent radiolucency on periapical radiography.[45] Compared to donor teeth with an open apex, the root resorption rate is higher when teeth with a closed apex are used.[40] In a cohort of 50 ATT third molars, 3 were lost due to root resorption during the 4-year follow-up. None of the root resorptions occurred before the second postoperative year. A significantly increased frequency of root resorption was found after 3 years.[28]

Limitations and Strengths

Because of the inherent limitations in the included studies, caution is warranted when interpreting the outcomes of this meta-analysis. First, the data were mainly from uncontrolled studies, which suggests a limited level of evidence. Second, the number and quality of included studies were insufficient. Third, the meta-analysis was based on disparate studies that were not matched for confounders.

To the best of our knowledge, this is the first systemic review of the outcomes of ATT of third molars with complete root formation. The results provide evidence of alternative treatments that could be used to counsel patients. Further comparative studies with long-term follow-up are needed.

Implications for Dental Practice

With appropriate patient selection, ATT of third molars with complete root formation could be a reasonable alternative option for tooth replacement.[31] A motivated, cooperative patient with good oral hygiene, in good general health, and with a willingness to attend review appointments is essential for success.[9] Although pulp healing is unexpected, periodontal healing should not be compromised while transplanting teeth with complete root formation.[5] With precise procedures and minimal damage to the PDL tissue, the esthetic and functional outcomes can be maximized.[23,34,46,53] ATT has favorable success and survival rates when the indication is appropriate and the treatment protocol is followed. Therefore, ATT of third molars with complete root formation is acceptable both therapeutically and economically.[28,30]

CONCLUSIONS

ATT of third molars with complete root formation is a reliable alternative for the replacement of a missing tooth and has a promising survival rate. The use of 3D techniques can improve the precision of the surgical procedure and reduce the complication rate, which makes long-term success more likely. An appropriate indication and patient selection are crucial for successful ATT of third molars with complete root formation. However, since the available published evidence is of a limited level of quality, caution is warranted when interpreting the outcomes of this review.

AUTHOR CONTRIBUTIONS

JH and ZC contributed to the conception and study design. JH, HX, and YG screened and reviewed the studies. JH, YG, and DL conducted the data extraction and statistical analysis. YG, YY, and DL assessed the quality of the included studies. SH, HZ, and XT checked the quality of the methodology. JH and HX drafted the manuscript. NL critically revised the manuscript. All authors approved the final version of the manuscript and its submitted form.

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