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Outcomes and Prognostic Factors of Absorbable Collagen Sponge-Assisted Apical Microsurgery: A Retrospective Cohort Study

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Abstract

Aims

Absorbable collagen sponge (ACS) is increasingly used as a bone void filler in apical microsurgery (AMS). However, studies on the outcomes and prognostic factors of ACS-assisted AMS remain limited. This retrospective study aimed to evaluate the outcomes and prognostic factors of ACS-assisted AMS using a time-to-event analysis and to identify prognostic factors associated with the time to success.

Methods

This retrospective cohort study included 91 teeth with 84 periapical lesions from 70 patients who underwent ACS-assisted AMS between January 2022 and December 2025, with a minimum follow-up of 6 months. All included patients had pre-operative and post-operative CBCT (follow-up: 6–42 months). The endpoint event was strict success, defined as CBCT-PAI ≤ 2 with no clinical symptoms. Time-to-event analysis was performed using the Kaplan-Meier method and Cox proportional hazards regression.

Results

Under the lenient criteria, the overall success rate was 96.4% (81/84). Under the strict criteria, the success rate was 66.7% (56/84). Lesion size ≤ 5 mm and anterior tooth location showed a significant association with success rate. In the time-to-event analysis, the cumulative probability of success was 87.1% at 36 months, with a median time to success of 17.0 months (95% CI: 13.5–20.5). In Cox univariate analyses, anterior tooth location, preoperative absence of symptoms, and lesion size≤5mm were associated with shorter time to success ($P < 0.05$), but only lesion size remained an independent prognostic factor of time to success in the multivariable Cox regression (HR: 4.91, 95% CI: 2.49–9.67, $P < 0.001$). The media time to success was 8.0 months (95% CI: 4.1–11.9) for lesion size≤5mm, compared with 19.0 months (95% CI: 15.5–22.4) for lesions > 5 mm.

Conclusion

ACS-assisted AMS achieved favorable outcomes, with a median time to success of 17.0 months. Anterior tooth and lesion size were associated with success rate. Lesion size were identified as an independent prognostic factor of time to success.

Clinical Relevance

This study demonstrates that ACS-assisted AMS achieves predictable healing, with a median time to success of 17.0 months. Lesion size≤5 mm predicts faster healing and a higher success rate, while anterior teeth also show a higher success rate. ACS represents a alternative material for periapical bone defect management.

1. Introduction

Apical microsurgery (AMS) is an effective tooth-preserving treatment for persistent periapical periodontitis, failed non-surgical treatment, and certain iatrogenic errors such as apical instrument separation, root perforation [1]. With the widespread use of microsurgical techniques, ultrasonic instruments and cone-beam computed tomography (CBCT), the success rate of modern AMS has improved significantly, with reported success rates ranging from 85% to 93% [2].

After root-end resection and curettage of the periapical lesion, a bone defect is often created. The quality of periapical bone healing remains one of the key determinants of long-term outcome [3]. To stabilise the blood clot and guide bone regeneration (GBR), bone graft materials or absorbable collagen sponge (ACS) are frequently placed into the defect.

Bone graft, typically a deproteinised bovine bone mineral (Bio-Oss®), exhibits excellent osteoconductive properties, maintains space within the bone defect, and provides a stable scaffold for the in-growth of new blood vessels and osteoblasts. Its slow resorption (usually lasting 6–12 months or longer) offers long-term support for bone remodelling [4,5]. The clinical efficacy of bone graft in AMS is supported by many researches [6–8].

Another type of filling material ACS is a major component of the extracellular matrix, offering good biocompatibility, hemostatic properties, and cell affinity. Its porous structure provides a favorable microenvironment for cell adhesion and proliferation, thereby supporting vascularization and osteoblast migration [9]. ACS is completely resorbable, typically within 4–8 weeks, and therefore leaves no permanent foreign material in the defect. Additionally, ACS is considerably less expensive than bone graft [10] (approximately 150 vs. 750 CNY). Nevertheless, the evidence base for ACS in AMS remains narrow. Evidence from other oral surgical procedures suggests potential benefits. ACS has shown favorable soft and hard tissue healing in immediate implant placement [11] and reduced alveolar osteitis in mandibular third-molar sockets [12], which indicating clot stabilization and enhanced early wound healing. Encouragingly, a 2023 randomized controlled trial reported that while a collagen-based filler in four-walled defects yielded higher rates of buccal cortical plate restoration compared with the control group (68.8% vs. 46.2%, $p = 0.243$), suggesting a potential benefit for bone regeneration [13]. Despite the widespread clinical use of ACS in bone defect management, its isolated application in AMS has not been systematically evaluated. To date, outcome data on ACS-assisted periapical healing remain limited.

In endodontics, cone-beam computed tomography (CBCT) is now widely used for its ability to produce high-resolution three-dimensional (3D) images that facilitate the assessment of tooth morphology, detection of periapical disease, and evaluation of treatment outcomes [14,15]. Although CBCT involves a higher radiation dose than conventional two-dimensional (2D) imaging, it improves diagnostic accuracy and provides a more reliable basis for assessing periapical healing [16].

To address the current research gap regarding the efficacy of ACS in AMS, the present study was undertaken to evaluate its clinical outcomes and prognostic factors. Most previous studies have focused on binary outcomes (healed vs. unhealed) at a single time point [3,17], which may oversimplify the dynamic nature of bone regeneration and provide insufficient guidance for postoperative follow-up

planning. Therefore, this study utilized CBCT-PAI and survival analysis to comprehensively assess ACS performance and guide clinical decision-making.

2. Materials and Methods

2.1 Ethic

- This retrospective cohort study was approved by the Medical Ethics Committee of the Stomatology Hospital, School of Stomatology, Zhejiang University School of Medicine (approval No. 2026-84).

2.2 Patient Selection

This retrospective study included patients who underwent apical microsurgery with ACS at the Department of Endodontics, Stomatology Hospital, Zhejiang University, between January 2022 to December 2025.

Inclusion criteria were:

1. Mature permanent teeth with a diagnosis of persistent apical periodontitis;
2. Apical microsurgery performed with root-end resection and filling, followed by placement of ACS into the periapical bone defects;
3. Availability of preoperative CBCT and at least one postoperative CBCT with a minimum follow-up of 6 months;
4. Complete clinical records including age, sex, symptoms (pain, swelling, sinus tract, tenderness, or mobility).

Exclusion criteria were:

(1) Systemic diseases affecting bone metabolism (e.g., uncontrolled diabetes, osteoporosis, long-term corticosteroid use);

1. Heavy smoking (> 10 cigarettes/day);
2. Pregnancy or lactation;
3. Teeth with severe periodontitis;
4. Defects where both ACS and bone graft were used in the same cavity, or with a barrier membrane;

(6) Postoperative CBCT only available before 6 months without any later follow-up or incomplete clinical records.

2.3 Lesion Type Definition

A periapical lesion was defined as a radiolucent area communicating with the root apex on CBCT.

1. Single-root lesion: periapical radiolucency originating from a single root;
2. Confluent lesion: periapical radiolucency originating from more than one roots.

- For subsequent analyses, each lesion was considered as the unit of analysis. In confluent lesions, the root-end resection angle and retrograde filling depth were measured based on the root with the largest periapical lesion diameter as determined on CBCT images.

2.4 Surgical Procedure

The operations were carried out by a team of senior endodontists using a standardized microsurgical protocol [18] under an operating microscope (Zeiss). After local anaesthesia with 4% articaine containing 1:100,000 epinephrine (Primacaine), a full-thickness mucoperiosteal flap was elevated. Ostectomy was performed to expose the root apex and the periapical lesion. The root end was resected perpendicular to the long axis by 3 mm. The resected surface was stained with methylene blue to identify any fractures or anatomical complexities. Root-end cavity preparation was done ultrasonically with an ultrasonic tip (B&L Biotech), and iRoot BP (Innovative BioCeramix) was placed in the retrograded root canal. The periapical bone cavity was thoroughly curetted to remove granulomatous tissue. The bone cavity was filled with a ACS (Bonanga). No barrier membrane was used. The flap was sutured, and immediate postoperative periapical radiograph confirmed material placement. Patients were provided with a postoperative instruction booklet, and the attending physician verbally reinforced the key precautions. They were advised to return for suture removal in 1–2 weeks and to attend follow-up visits at 3- to 6-month intervals thereafter.

2.5 Radiographic Assessment and CBCT-PAI Scoring

- Preoperative and postoperative CBCT scans were obtained using the CBCT device model (NewTom). Scanning parameters were: tube voltage 110 kVp, tube current 8 mA, voxel size 0.2 mm, field of view 8 × 8 cm. All scans were performed with the same settings to ensure consistency.
- All measurements (maximum lesion diameter on preoperative and follow-up CBCT images, retrograde filling depth, and root-end resection angle) were performed twice, and the mean values were used for analysis.
- Postoperative periapical healing was assessed using the CBCT periapical index (CBCT-PAI), which classifies periapical lesions based on the maximum diameter according to the following criteria: 0 = Intact periapical bone structures; 1 = 0.5-1 mm (widened periodontal ligament space); 2 = 1–2 mm; 3 = 3–4 mm; 4 = 4–8 mm; 5 = > 8 mm [19,20].

2.5 Measurement and Reliability

- To assess the reproducibility of the lesion size, root-end resection angle, and retrograde filling depth, they were measured twice by each of two senior endodontists on a random subset of 20 lesions from the study cohort. The intra-class correlation coefficients (ICCs) with 95% confidence intervals for intra-observer agreement were 0.94 (0.84–0.98) for lesion diameter, 0.93 (0.83–0.97) for

resection angle, and 0.94 (0.85–0.98) for retrograde filling depth. For inter-observer agreement, the ICCs were 0.96 (0.90–0.99), 0.92 (0.82–0.97), and 0.88 (0.70–0.95), respectively. These values indicated excellent reliability for all three parameters, supporting the validity of the measurement protocol.

2.7 Outcome Definitions

2.7.1 Radiographic Healing Categories

Radiographic healing were categorized based on the CBCT-PAI score and the dynamic changes in lesion size between pre- and postoperative images on serial postoperative images [21]:

Healed: CBCT-PAI score ≤ 2 at the final follow-up

Healing in progress: CBCT-PAI score ≥ 3 at the final follow-up, with a reduction in the maximum diameter of the periapical radiolucency compared with preoperative images;

Not healed: CBCT-PAI score ≥ 3 at the final follow-up, with the periapical radiolucency showing no significant change or enlargement compared with preoperative images.

2.7.2 Clinical Success

Preoperative clinical symptoms (pain, swelling, sinus tract, tenderness, and mobility) were recorded from the initial examination. At follow-up, clinical success was defined as the complete resolution of these symptoms.

2.7.3 Lenient vs. Strict Criteria

Treatment outcomes were evaluated using both lenient and strict criteria, following the framework established in previous endodontic outcome studies [15,22]:

Lenient criteria: Success was defined as either radiographic healed or healing in progress, both with no clinical symptoms. Failure was defined as not healed or presenting with clinical symptoms.

Strict criteria: Success was defined exclusively as radiographic healed with no clinical symptoms. All other outcomes, including radiographic healing in progress, not healed, or symptomatic cases, were classified as failure.

For the success rate and time-to-event analysis, the strict criteria were applied, with success serving as the endpoint event.

2.8 Statistical Analysis

- All statistical analyses were performed using SPSS version 27.0 (IBM). Continuous variables were expressed as mean with standard deviation (SD) or medians with interquartile ranges (IQRs), and

categorical variables as frequencies and percentages. Missing data were not imputed, and analyses were performed on available cases.

In this study, success rate was defined as the proportion of lesions that achieved strict success at the final follow-up. Cumulative probability of success was defined as the time-dependent probability of achieving success.

2.8.1Univariate Analyses and Binary Logistic Regression Analysis

To identify factors associated with the success rate, univariate analyses were first performed using the chi-square test or Fisher-Freeman-Halton exact test (when > 20% of cells had expected frequencies < 5) for categorical variables. Variables with $P < 0.10$ in the univariate analysis, together with clinically important factors, were entered into a multivariable binary logistic regression model using the enter method to identify independent prognostic factor of strict success rate. Results were reported as odds ratios (ORs) with 95% confidence intervals (CIs). A two-sided $P < 0.05$ was considered statistically significant.

2.8.2 Definition of Time-to-Event Variable

Time-to-event was calculated in months from the date of surgery to the first documented date of success for patients who achieved the endpoint, or to the date of the last follow-up visit for censored cases. The endpoint event was defined as strict success. For cases that met the success criteria at a given follow-up visit, the endpoint was assigned only after confirmation at a subsequent visit, including both clinical and CBCT assessments, to ensure that the success was sustained and not transient. If a case later reverted to failure, the event was censored at the last confirmed success visit.

2.8.3 Survival Analyses

Cumulative probability of success were estimated using the Kaplan-Meier method. To identify potential predictors of time to success, each variable was first evaluated using univariate Cox proportional hazards regression. Variables with $P < 0.10$ and clinically important factors were entered into a multivariable Cox proportional hazards regression model using the enter method. Results were reported as hazard ratios (HRs) with 95% confidence intervals (CIs). Since the endpoint event was defined as strict success, an HR > 1 indicated a shorter time to success. Variables identified as statistically significant in the multivariable model were further visualized using Kaplan-Meier curves, and differences between groups were compared using the log-rank test. A two-sided P-value < 0.05 was considered statistically significant.

3 Results

3.1 Descriptive Results

- The flowchart was shown in Fig. 1. Of 513 patients who underwent AMS during the study period, 112 were treated with ACS. Among them, 70 patients had a minimum postoperative CBCT follow-up of 6 months and were included in the final analysis. These 70 patients contributed a total of 91 teeth, which were further categorized into 84 independent periapical lesions based on the lesion type definitions (single-root or confluent lesions). Specifically, 17 patients contributed 2 teeth each, 3 patients contributed 3 teeth each, 1 patient contributed 4 teeth, and the remaining patients each contributed one tooth. These lesions comprised 62 single-root lesions and 22 confluent lesions. The majority of lesions were in patients aged ≤ 40 years (56/84, 66.7%), predominately observed in female patients (47/84, 56.0%), and located in the anterior teeth (69/84, 82.1%) (Table 1). The mean follow-up duration was 17.1 ± 9.1 months (median: 17.0 months; IQR: 10.0-22.5 months). The overall follow-up period ranged from 6 to 41 months.

According to the lenient criteria, the overall success rate of ACS-assisted AMS was 96.4% (81/84). The three failures were attributed to the following: (1) one tooth was extracted due to root fracture; (2) one tooth developed persistent mobility; and (3) one tooth showed no radiographic healing, with the periapical lesion demonstrating a progressive increase in size compared with the preoperative images.

Under the strict criteria, the overall success rate was 66.7% (56/84). The remaining 28 lesions were classified as failures, all of which exhibited a PAI score ≥ 3 at the final follow-up. Among these, 25 lesions were categorized as “healing in progress” (showing a reduction in lesion size, but with PAI ≥ 3) with no clinical symptoms, while the other two lesions presented with clinical symptoms, and another teeth was extracted at the final follow-up.

3.2 Factors associated with success rate: univariate analysis and binary logistic regression analysis

In the univariate analysis, tooth position (anterior: 76.8% vs. posterior: 20.0%), lesion size (≤ 5 mm: 100% vs. >5 mm: 58.8%), and lesion type (single-root: 75.8% vs. confluent: 40.9%) were significantly associated with the success rate (all $P < 0.05$) (Table 1).

Table 1
Univariate analysis of factors associated with success rate in ACS-assisted AMS

	Variables	N	Success (n,%)	Failure (n,%)	P value
Patient-related information					
Age	≤ 40	56	37(66.1)	19(33.9)	0.53
	> 40	28	19(67.9)	9(32.1)	
Gender	Male	37	28(75.7)	9(24.3)	0.16
	Female	47	28(59.6)	19(40.4)	
Arch type	Maxilla	75	52(69.3)	23(30.7)	0.13
	Mandible	9	4(44.4)	5(55.6)	
Teeth position	Posterior	15	3(20.0)	12(80.0)	0.00*
	Anterior	69	53(76.8)	16(23.2)	
Preoperative-related information					
Preoperative symptoms	Present	66	42(63.6)	24(36.4)	0.20
	Absent	18	14(77.8)	4(222.2)	
Root filling	Inadequate	67	45(67.2)	22(32.8)	0.53
	Adequate	17	11(64.7)	6(35.3)	
Restoration	Crown	32	23(71.6)	9(28.1)	0.42
	Filling	42	33(63.5)	19(36.5)	
Lesion size	d>5mm	68	40(58.8)	28(41.2)	0.002*
	d≤5mm	16	16(100.0)	0(0.0)	
Cortical destruction	Absent	19	14(73.7)	5(26.3)	0.46
	Present	65	42(64.6)	23(35.4)	
Lesion type	Fused	22	9(40.9)	13(59.1)	0.003*
	Single-root	62	47(75.8)	15(24.2)	
Intraoperative-related information					
Root resect angle	>10	53	37(69.8)	16(30.2)	0.42
	≤ 10	31	19(61.3)	12(38.7)	
Retrograde-filling depth	<3	34	22(64.7)	12(35.7)	0.75

	Variables	N	Success (n,%)	Failure (n,%)	P value
Patient-related information					
	≥ 3	50	34(68.0)	16(32.0)	

In the multivariable logistic regression analysis, due to complete separation between lesion size and treatment outcome (all cases with a diameter ≤ 5 mm achieved treatment success), this variable was not included in the multivariable logistic regression model. Its univariate analysis results (P = 0.002) have been described previously. Anterior (OR: 10.7, 95%CI: 2.2–50.5) was associated with a higher success rate in the multivariable logistic regression analysis (Table 2).

Table 2
Multivariable logistic regression analysis of factors associated with success rate in ACS-assisted AMS

Tooth position	Variables	Adjusted OR (95% CI)	P
	Posterior	**1**	**0.003***
	Anterior	10.7(2.2–50.5)	
Lesion type	Confluent	1	0.26
	Single	2.0(0.6–7.2)	
Root resection angle	>10	1	0.17
	≤ 10	2.1(0.7–6.3)	
Retrograde filling depth	<3mm	1	0.91
	≥ 3mm	0.9(0.3–2.8)	

3.3 Survival analysis for time to success

Among the 56 lesions that achieved the endpoint, the median time to success was 12.0 months (IQR: 7.25-19.0). For the 28 lesions that were censored, follow-up was terminated at a median time of 13.0 months (IQR: 6.0–28.0) without meeting the success criteria.

The Kaplan-Meier curve for the entire cohort is presented in Fig. 2. Since the endpoint event was defined as strict success, the vertical axis represents the cumulative probability of success (the proportion of lesions that have achieved the endpoint over time), calculated as 1 minus the survival function. The curve demonstrated a stepwise upward trend over the follow-up period, reflecting the progressive accumulation of successful cases.

The media time to success was 17.0 months (95%CI: 13.5–20.5) overall. The cumulative probability of success at 6, 12, and 18 months were 13.1% (95% CI: 5.9%-20.3%, N = 11), 37.6% (95% CI: 26.6%-48.6%,

N = 29), and 55.8% (95% CI: 43.8%-67.8%, N = 40), respectively. At approximately 24 months (based on the 23-month time point), the cumulative probability of success was 71.8% (95% CI: 60.0%-83.6%, N = 40). At approximately 30 months (based on the 28-month time point), the cumulative probability of success was 79.3% (95% CI: 67.9%-90.7%, N = 51). At 36 months, the cumulative probability of success was 87.1% (95% CI: 75.9%-98.3%, N = 53), but this estimate should be interpreted with caution due to the small number of remaining cases at this time point.

The univariate Cox regression analysis identified several variables potentially associated with a faster time to success in ACS-assisted AMS, including anterior teeth (HR:3.87, 95%CI: 1.2-12.43), preoperative absence of symptoms (HR: 2.19, 95% CI:1.18–4.09), and lesion size ≤ 5 mm (HR: 5.38, 95%CI: 2.8-10.33) (Table 3)

Table 3
Univariate Cox regression analysis for time to success in ACS-assisted AMS

	Variables	N	Success (n,%)	Failure (n,%)	Unadjusted HR (95% CI)	P value
Patients-related information						
Age	≤ 40	56	37(66.1)	19(33.9)	1	0.83
	> 40	28	19(67.9)	9(32.1)	0.94(0.53–1.06)	
Gender	Male	37	28(75.7)	9(24.3)	1	0.91
	Female	47	28(59.6)	19(40.4)	0.97(0.56–1.67)	
Arch type	Maxilla	75	52(69.3)	23(30.7)	1	0.73
	Mandible	9	4(44.4)	5(55.6)	0.83(0.30–2.33)	
Teeth position	Posterior	15	3(20.0)	12(80.0)	1	0.02*
	Anterior	69	53(76.8)	16(23.2)	3.87(1.2–12.43)	
Preoperative-related information						
Preoperative symptoms	Present	66	42(63.6)	24(36.4)	1	0.01*
	Absent	18	14(77.8)	4(22.2)	2.19 (1.18–4.09)	
Root canal filling	Inadequate	67	45(67.2)	22(32.8)	1	0.33
	Adequate	17	11(64.7)	6(35.3)	0.71(0.35–1.41)	
Restoration	Crown	32	23(71.6)	9(28.1)	1	0.27
	Filling	42	33(63.5)	19(36.5)	0.73(0.42–1.28)	
Lesion size	d>5mm	68	40(58.8)	28(41.2)	1	0.00*
	d≤5mm	16	16(100.0)	0(0.0)	5.38(2.8–10.33)	
Cortical destruction	Absent	19	14(73.7)	5(26.3)	1	0.48
	Present	65	42(64.6)	23(35.4)	0.80(0.43–1.490.48)	
Lesion type	Confluent	22	9(40.9)	13(59.1)	1	0.06
	Single-root	62	47(75.8)	15(24.2)	1.99(0.97–4.08)	
Intraoperative-related						
Root resect angle	>10	53	37(69.8)	16(30.2)	1	0.76
	≤ 10	31	19(61.3)	12(38.7)	0.92(0.52–1.61)	

	Variables	N	Success (n,%)	Failure (n,%)	Unadjusted HR (95% CI)	P value
Patients-related information						
Retrograde-filling depth	≥ 3	50	34(68.0)	16(32.0)	1	0.13
	<3	34	22(64.7)	12(35.7)	0.66(0.38–1.14)	

#Hazard ratios (HR) > 1 favor a shorter time to success, since the endpoint event was defined as success under strict criteria.

Multivariable Cox regression analysis was performed with 4 covariates and 56 events (EPV = 14), meeting the recommended sample size criterion to minimize the risk of overfitting [23]. This model (Table 4) revealed that a preoperative lesion diameter ≤ 5 mm was independently associated with a faster time to success (HR = 4.91; 95% CI, 2.49–9.67; P < 0.001). Tooth position, Lesion type, and preoperative symptoms were not significantly associated with time to success, suggesting that its univariate effect was largely confounded by lesion-related factors.

Table 4
Multivariable Cox regression analysis for time to success in ACS-assisted AMS

Tooth position	**Variables**	**Adjusted HR (95% CI)**	**P**
	Posterior	**1**	**0.05**
	Anterior	3.42(0.98)	
Lesion type	Confluent	1	0.86
	Single-root	1.07(0.49–2.37)	
Preoperative symptoms	Present	1	0.11
	Absent	1.71(0.89–3.26)	
Lesion size	>5mm	1	0.00*
	≤ 5mm	4.91(2.49–9.67)	

#Hazard ratios (HR) > 1 favor a shorter time to success, since the endpoint event was defined as success under strict criteria.

The Kaplan-Meier curve for lesion size was shown in Fig. 3. The median time to success for lesions ≤ 5 mm was 8.0 months (95% CI: 4.1–11.9), compared with 19.0 months (95% CI: 15.5–22.4) for lesions > 5 mm. The log-rank test was used to compare the two groups ($\chi^2 = 33.3$, P < 0.001)

4 Discussion

This is the first study to quantify the time to success of ACS-assisted AMS using a time-to-event analysis framework. Understanding the time to success helps establish evidence-based follow-up schedules and manage patient expectations [21,24]. Accordingly, this study employed Kaplan-Meier survival analysis and Cox proportional hazards regression to characterize the success rate of ACS-treated periapical lesions and to identify prognostic factors associated with the time to success, providing a more comprehensive assessment of the regenerative process than conventional binary evaluations.

In the present cohort, the overall success rate was 96.4% (81/84) under lenient radiographic criteria and 66.7% (56/84) under strict criteria at the final follow-up. The lenient-criteria outcome is numerically comparable to the highest benchmarks documented in long-term endodontic microsurgery series (e.g., 94.9%-96.2%) [25, 26], whereas the strict-criteria rate aligns closely with the 59.5% healing rate reported in a medium-to-long-term CBCT-based study that employed identical stringent radiological endpoints [27].

The success rate under strict criteria was significantly lower than that under lenient criteria, a difference mainly attributable to the classification of “healing in progress” cases: 25 asymptomatic lesions with PAI ≥ 3 but reduced lesion size, which were counted as success under lenient criteria, were classified as failures under strict criteria. This observation suggests that complete radiographic healing of periapical bone defects may require an extended observation period, and that some lesions had not yet achieved complete bone remodeling within the current follow-up window.

The cumulative probability of success for ACS-assisted AMS in our cohort was 87.1% at 36 months, compared with 72.3% reported in another study at a similar follow-up time point. [28]. Furthermore, our results are consistent with the upper range of published outcomes, as another study reported an estimated 5-year success rate of 91.6%.[29] The media time to success was 17.0 months (95%CI: 13.5%-20.5%).

The favorable outcomes observed with ACS are likely attributable to its good biocompatibility, hemostatic properties, and cell affinity. [9] Its porous architecture mimics the natural extracellular matrix, providing a three-dimensional scaffold that supports cell adhesion, proliferation, and differentiation[30]. This osteoconductive environment [31], combined with its hemostatic properties that stabilize the blood clot within the bony defec, may create favorable conditions for early angiogenesis and subsequent bone formation[30,32]. However, we acknowledge that these mechanistic inferences are extrapolated from the material's known physicochemical properties and in vitro evidence, rather than directly demonstrated in our clinical cohort. The critical clinical takeaway remains that ACS, as a simple and biologically compatible filler, yields kinetic outcomes that are statistically and clinically consistent with established benchmarks, thereby supporting its reliability as a primary bone void filler in modern microsurgical practice, particularly when cost or patient preference against xenogeneic materials is considered.

The favorable success status also reflect the benefits of strict inclusion criteria, exclusion criteria, and contemporary microsurgical protocols. The routine use of the surgical operating microscope, ultrasonic instruments, and bioceramic root-end filling materials has collectively minimized technical variability and optimized the biological environment for periapical tissue repair [33,34]. Consequently, traditional technical factors such as root-end resection angle and retrograde filling depth, which historically considered prognostic determinants, appear to have lost their relative impact in the modern apical surgeon [35,36]. This is consistent with recent evidence suggesting that when standardized microsurgical principles are rigorously applied, the influence of isolated technical parameters on healing outcomes becomes negligible, allowing host- and lesion-related biological factors to assume the primary prognostic role[37].

Our study demonstrated that a preoperative lesion size ≤ 5 mm was significantly associated with higher overall success rate and a faster time to success in ACS-asisted AMS. This finding is consistent with many evidences indicating that smaller periapical lesions generally exhibit more favorable healing dynamics following endodontic surgery. Several studies have reported that lesion size is one of the most reliable predictors of treatment outcome, with smaller defects showing higher healing rates and shorter healing times compared with larger lesions [3,36]

The biological plausibility of this observation is well-supported. Smaller bone defects require less volume of new bone formation to achieve complete radiographic resolution, and they are less likely to have compromised cortical bone integrity or extensive soft tissue infiltration [38]. Furthermore, smaller lesions may be associated with less extensive inflammatory involvement of the surrounding bone marrow spaces, thereby facilitating more rapid repopulation by osteoprogenitor cells and angiogenesis during the early stages of healing [39].

In the present study, anterior tooth was also identified as prognostic factor associated with a higher success rate in univariate analyses and multivariable binary logistic regression, due to better surgical accessibility, shorter root length with more straightforward canal anatomy, and richer vascular supply from the adjacent labial bone plate [40].

The resolution of apical periodontitis is a time-dependent dynamic process.This observation has been well documented in literature [28,29,41]. The character underscores that traditional binary outcome measures (healed vs. unhealed) assessed at a single time point may insufficiently capture the dynamic nature of periapical bone regeneration and may underestimate the true healing potential of treated teeth.

In the present study, the overall success rate under strict criteria was 66.7% (56/84), whereas the Kaplan-Meier estimated cumulative probability of success were 55.8%, 71.8%, and 79.3% at 18, 24, and 30 months, respectively. The apparent discrepancy between these figures is not a contradiction, but rather a consequence of the different ways in which the two methods handle censored data.

The overall success rate included all 84 lesions in the denominator, treating 28 censored cases as failures simply because they had not achieved success by their last follow-up, leading to a systematic

underestimation. In contrast, the Kaplan-Meier method retains censored cases in the risk set until their last observation and removes them only thereafter, avoiding the bias of arbitrarily classifying unknown outcomes as failures. Thus, in retrospective studies with variable follow-up durations and non-negligible censoring rates, cumulative probability of success provide a more accurate reflection of long-term treatment outcomes than a single fixed time-point success rate. The cumulative probability of success should therefore be considered the primary reference for interpreting treatment efficacy in this cohort.

In our study, we employed a time-to-event analysis framework. This approach allowed us to utilize the full spectrum of follow-up data (ranging from 6 to 41 months) thereby maximizing the statistical efficiency of our relatively modest sample size (84 lesions)[21].

Collectively, these findings show that ACS-assisted AMS yields predictable outcomes across a range of lesion sizes, and that the use of a time-to-event framework provides a more clinically informative assessment. ACS represents a simple, cost-effective, and biologically sound alternative for periapical bone defect management, particularly for patients with economic constraints or those who decline xenografts. When performed under standardized microsurgical principles, ACS-assisted EMS achieves success rates that compare favorably with the highest reported outcomes in the literature, supporting its routine application in clinical practice.

Several limitations of this study should be acknowledged.

1. The retrospective design may introduce selection or information bias due to variability in clinical records. .
2. The relatively modest sample size (84 lesions) may limit statistical power, particularly in subgroup analyses.
3. The follow-up period varied considerably (range: 6–41 months), with a median of 17 months and a censoring rate of approximately 33.3% (28/84). While the Kaplan-Meier analysis appropriately accounts for censored data, the limited follow-up duration may still be insufficient to capture late healing reversals or to confirm long-term stability, as periapical healing can continue beyond 5 years post-surgery.
4. The absence of a control group limits our ability to attribute outcomes solely to ACS.
5. All procedures were performed by senior endodontists in a single academic center, which may limit generalizability to other settings or less experienced operators.

- Future prospective studies with larger sample sizes, standardized follow-up protocols, longer observation periods, and patient-reported outcome measures are warranted to validate these findings and further elucidate the role of ACS in AMS.

Declarations

Competing Interests

The authors declare that they have no competing interests.

Ethics Approval

This retrospective cohort study was approved by the Medical Ethics Committee of the Stomatology Hospital, School of Stomatology, Zhejiang University School of Medicine (approval No. 2026-84). Informed consent was waived due to the retrospective nature of the study.

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Author Contribution

Yunjie Zhu designed the study, performed CBCT measurements, statistical analysis, and drafted the manuscript; Jinghao Hu contributed to data collection, Jing Zhang contributed to clinical evaluation; Shuli Deng contributed to manuscript revision. All authors reviewed and approved the final version.

Data Availability

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

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Figures

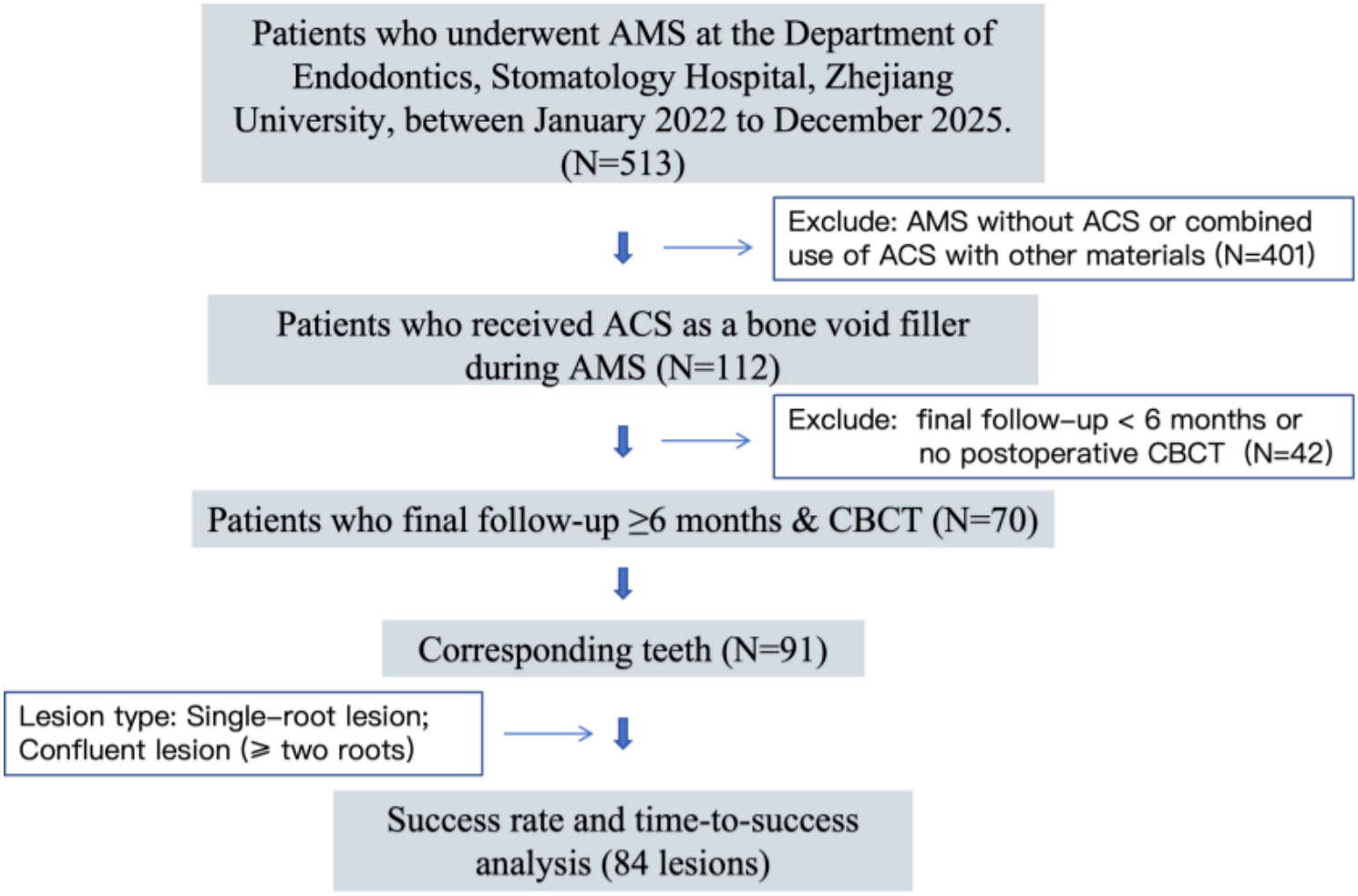


Figure 1

Study flowchart. A total of 513 patients underwent apical microsurgery during the study period. After excluding patients, 84 lesions with 91 teeth from 70 patients were included in the final analysis.

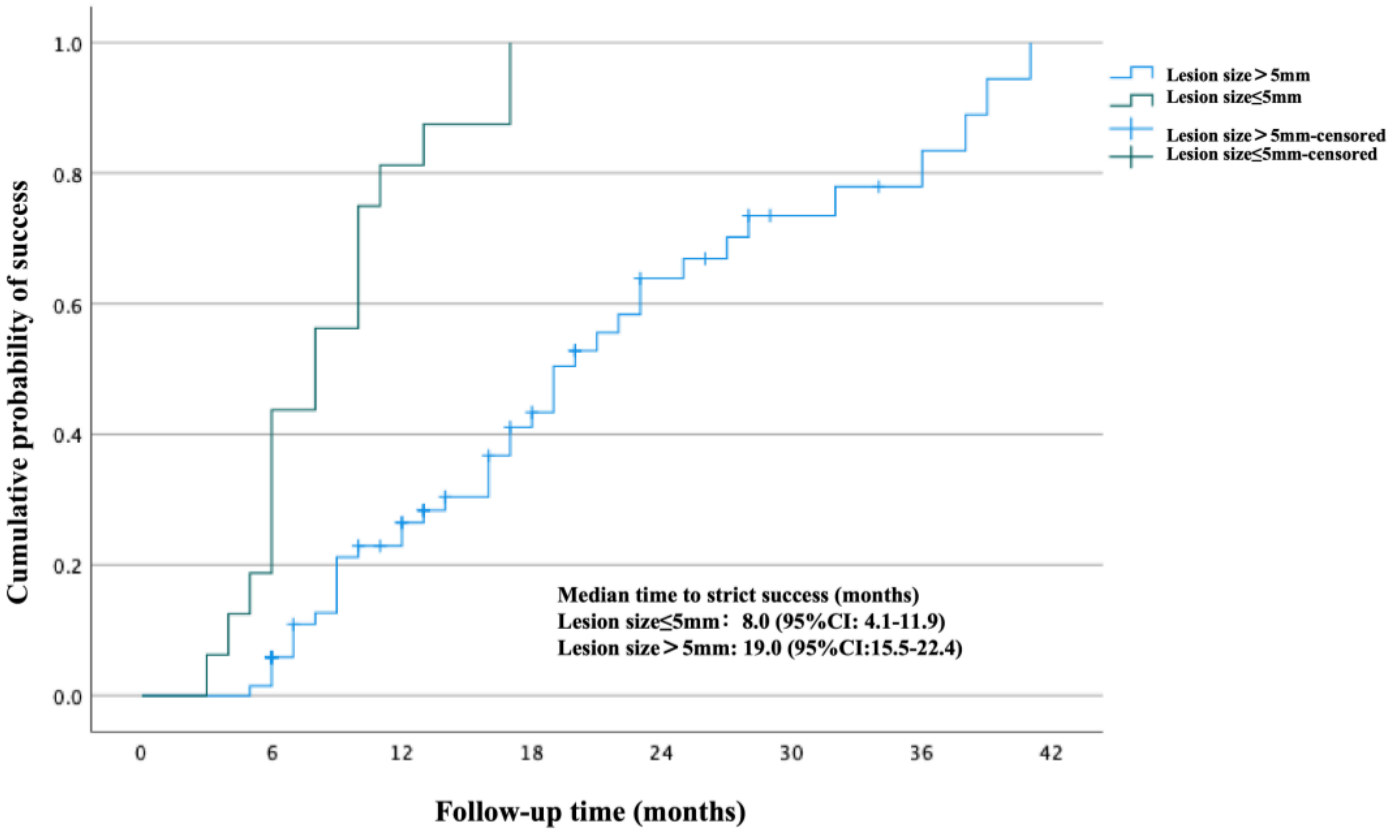
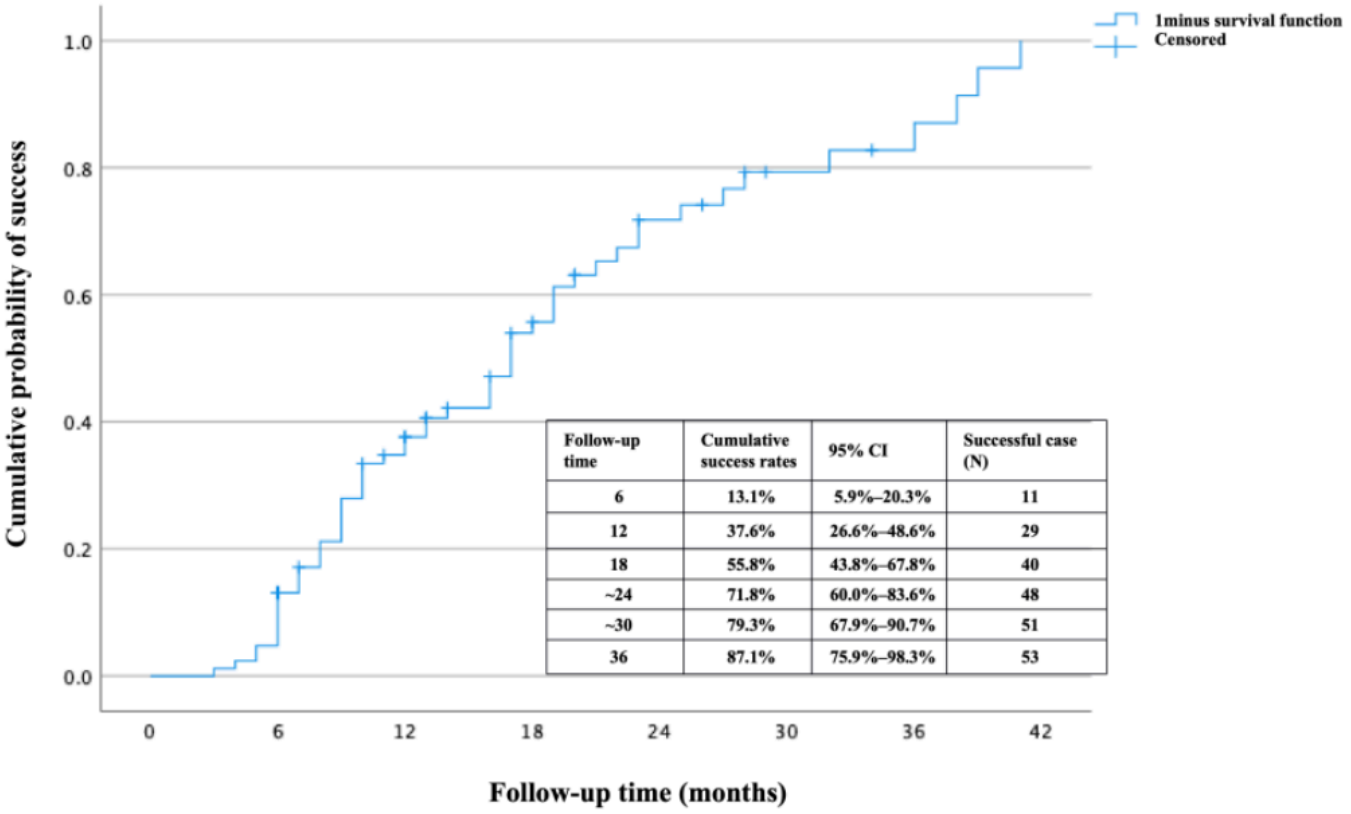


Figure 2

Kaplan-Meier cumulative probability of success curves stratified by lesion diameter (≤5 mm vs. >5 mm). The log-rank test confirmed a statistically significant difference between the two groups ($\chi^2 = 33.3$, $P < 0.001$). Vertical ticks indicate censored cases.



Follow-up time	Cumulative success rates	95% CI	Successful case (N)
6	13.1%	5.9%–20.3%	11
12	37.6%	26.6%–48.6%	29
18	55.8%	43.8%–67.8%	40
~24	71.8%	60.0%–83.6%	48
~30	79.3%	67.9%–90.7%	51
36	87.1%	75.9%–98.3%	53

Figure 3

Kaplan-Meier curve for overall cumulative probability of success. The event was defined as strict success. The vertical axis represents the cumulative probability of success, calculated as 1minus survival function. Vertical ticks indicate censored cases.