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Original Article

Efficacy of microwave *in situ* ablation combined with intralesional curettage for locally aggressive benign bone tumors based on MSTS scores, bone healing time, and recurrence rate

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Abstract: Objective: To compare the clinical efficacy of microwave *in situ* ablation (MWA) combined with intralesional curettage versus intralesional curettage alone for locally aggressive benign bone tumors, including giant cell tumor of bone, aneurysmal bone cyst, and chondroblastoma, with a focus on local recurrence control, limb function, and bone healing. Methods: This retrospective cohort study included 284 patients who were divided into a combined group (MWA plus curettage, n=156) and a control group (curettage alone, n=128). Baseline characteristics, perioperative outcomes, complications, local recurrence, bone healing status, and Musculoskeletal Tumor Society (MSTS) scores were compared. Recurrence-free survival (RFS) was analyzed using Kaplan-Meier method, and independent risk factors were evaluated using Cox regression analysis. Subgroup analyses were performed based on pathologic type and lesion size. Results: The combined group had a significantly lower local recurrence rate than the control group (7.1% vs. 18.0%, P=0.008) and an improved RFS HR=0.38, 95% CI: 0.19-0.79). MSTS scores were significantly higher in the combined group at all postoperative time points (all P>0.05). Bone healing time was shorter in the combined group (4.3±1.5 vs. 5.0±1.5 months, P<0.001), with a lower rate of delayed union (5.8% vs. 18.8%, P=0.001). Multivariable analysis identified MWA as an independent protective factor (HR=0.25, P<0.001), while soft tissue involvement, lesion diameter >6 cm, and extensive cortical destruction were independent risk factors. Subgroup analyses showed consistent benefits in larger lesions. Conclusion: MWA combined with intralesional curettage significantly reduces local recurrence, improves limb function, and accelerates bone healing compared to curettage alone. It represents a safe and effective limb-salvage strategy for locally aggressive benign bone tumors.

Keywords: Locally aggressive benign bone tumors, giant cell tumor of bone, microwave ablation, intralesional curettage, local recurrence, limb function

Introduction

Locally aggressive benign bone tumors, such as giant cell tumor of bone (GCTB), aneurysmal bone cyst (ABC), and chondroblastoma, are not high-grade malignancies but can invade adjacent tissues, destroy the cortical bone, extend into surrounding soft tissues, and cause pathologic fractures. When these tumors involve periarticular protective tissues, they can lead to persistent pain, impaired joint function, and reduced quality of life [1, 2]. GCTB predominantly affects young adults and typically arises in the epiphyses or metaphyses of long bones, with the knee and distal radius being the most common sites [3]. Achieving tumor control while preserving joint function requires a meticulous approach [3, 4]. Recently, there has been a shift toward multidisciplinary strategies emphasizing personalized, risk-adjusted treatment for aggressive bone tumors [4, 5]. For periarticular lesions, the primary challenge is to minimize local recurrence risk without compromising functional outcomes due to extensive surgical resection.

Intralesional curettage remains a fundamental limb-salvage surgical approach for locally agg-

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ressive benign bone tumors in contemporary clinical practice [5]. This technique yields favorable functional results by preserving the original bone architecture and joint integrity. However, the limitations of curettage alone are well recognized: tumor margins are often irregular, making complete excision of the tumor wall and elimination of microscopic residuals. This is challenging, particularly in Campanacci grade III tumors or those involving surrounding soft tissues. This contributes to higher local recurrence rates [6]. Consequently, many medical centers have adopted standardized protocols combining extended curettage with local adjuvant therapies and reconstruction of resulting bone defects, based on the premise that these adjuvants enhance local control by reducing residual tumor cells.

Chemical ablation (phenol or absolute alcohol), cryotherapy (liquid nitrogen), and high-speed burring are commonly used local adjuvants. Systematic reviews and meta-analyses have shown that cryotherapy and other adjuvants may reduce local recurrence [7, 8], but complications such as fracture, infection, skin necrosis, and nerve injury must also be considered. Technical variations between studies may limit the consistency and generalizability of current evidence. Additionally, questions remain regarding the optimal combination of adjuvants, their indications, and their effects on bone healing. No comparative studies with consistent conclusions have been reported to date. There is an unmet need for more controllable, reproducible local ablation techniques with a manageable complication profile for limb-salvage treatment of aggressive benign bone tumors.

Numerous specialists worldwide have focused on microwave *in situ* ablation (MWA), a thermal ablation technique that uses electromagnetic wave energy to induce oscillation of water molecules in tissues, leading to irreversible thermal damage and coagulative necrosis of tumors [9]. MWA offers advantages over traditional local adjuvants, including rapid heating, customizable ablation areas, and reduced impact on high-impedance tissues. By controlling temperature and duration, ablation effects can be precisely regulated. In recent years, MWA has been increasingly applied in bone tumor treatment, with promising results for local management, particularly as an adjunct during surgery for giant cell tumors of bone (GCTB) [10, 11]. A multicenter retrospective study indicated that MWA-assisted intralesional curettage, combined with other treatments, achieved favorable local control and functional outcomes for Campanacci grade III GCTB of the distal radius [10], supporting the use of MWA in high-risk periarticular lesions. Additionally, with the growing use of preoperative denosumab to reduce tumor size, some researchers have explored the combination of denosumab, MWA, and curettage, suggesting this strategy may improve joint preservation rates and local control [11].

Despite these advances, existing data on MWA for locally aggressive benign bone tumors remain scarce. Most studies are single-center retrospective analyses or case series with small sample sizes and variable follow-up durations. Standardization is lacking in the definition and measurement of local recurrence, bone healing, and functional assessments such as MSTS scores, making comparisons difficult [12]. Furthermore, factors including pathologic subtype, lesion size, and soft tissue involvement are strong predictors of recurrence and functional outcomes, requiring validation of their independent impacts through more sophisticated statistical models. Additionally, long-term studies on ABC and chondroblastoma indicate that factors like anatomic location, surgical approach, and local treatment methods significantly affect recurrence rates and complications [13, 14]. Enhancing risk stratification and individualizing treatment plans is therefore crucial.

In this context, we aimed to compare the clinical outcomes of MWA plus curettage versus curettage alone for aggressive nonmalignant bone lesions. The primary endpoints were local recurrence control, limb functional recovery (assessed by MSTS scores), and bone healing indices (healing time and delayed union rate). Multivariable analyses were performed to identify independent risk factors for local recurrence, and subgroup analyses were conducted by pathologic type and lesion size. We sought to provide more reliable evidence for limb-salvage strategies in these tumors, aligning with current guidelines that prioritize tumor control and functional preservation [4, 5].

Materials and methods

Sample size calculation

According to published literature [3], the local recurrence rate of bone tumors treated with intralesional curettage alone is approximately 18%, whereas MWA combined with curettage may reduce this to approximately 7%. The sample size was calculated using the Schoenfeld formula with $\alpha=0.05$ and power $(1-\beta)=0.80$. The required number of events was estimated as $d=4\times(Z\alpha/2+Z\beta)^2/[\ln(HR)]^2$, where $HR=p2/p1=0.07/0.18\approx0.389$, $Z\alpha/2=1.96$, and $Z\beta=0.8416$. This yielded $d\approx35$ events. Thus, the total sample size was $N=2d/(p1+p2)\approx281$. A 10% loss to follow-up was accounted for, resulting in a minimum required sample size of 313 patients.

Inclusion and exclusion criteria

Inclusion criteria: (1) Age ≥18 and ≤70 years; (2) Imaging diagnosis of bone tumor by X-ray, computed tomography (CT), or magnetic resonance imaging (MRI), with postoperative pathological confirmation of GCTB, ABC, chondroblastoma, or other locally aggressive benign bone tumors; (3) First-time surgical treatment; (4) Underwent intralesional curettage with or without MWA; (5) Complete clinical and follow-up data.

Exclusion criteria: (1) Concurrent malignancy at another site; (2) Previous surgery at the same location; (3) Severe cardiac, pulmonary, hepatic, or renal dysfunction; (4) Hematologic or coagulation disorders; (5) Pregnancy or lactation; (6) <12 months or incomplete follow-up data; (7) Unable to complete standard treatment and follow-up for other reasons.

General information

This retrospective cohort study collected clinical data from patients who underwent surgical treatment at the Department of Orthopedic Oncology of Gansu Provincial Cancer Hospital between January 2018 and February 2022. All included cases were pathologically confirmed as locally aggressive benign bone tumors treated with limb-salvage intralesional surgery. After applying the inclusion and exclusion criteria, 284 patients were ultimately enrolled and divided into two groups according to the surgical approach: the combined group (MWA plus intralesional curettage, n=156) and the control group (intralesional curettage alone, n=128). This study was approved by the Medical Ethics Committee of Gansu Provincial Cancer Hospital, and written informed consent was waived due to its retrospective nature.

Clinical data collection

Baseline data included age, sex, body mass index (BMI), pathological tumor type, lesion location, whether the lesion was periarticular to the knee, maximum lesion diameter, degree of cortical destruction, presence of extensive cortical destruction, soft tissue infiltration, preoperative pathological fracture, history of diabetes mellitus, history of hypertension, and American Society of Anesthesiologists (ASA) classification.

Intraoperative indices included intraoperative blood loss, defect reconstruction method (bone cement filling only, autograft/allograft bone grafting, or combined cement and bone graft reconstruction), internal fixation use, and operative time.

Postoperative recovery and complications included drainage volume, duration of drain placement, time to first ambulation, postoperative hospital stay, wound infection, delayed wound healing, and deep vein thrombosis (DVT).

Follow-up data included follow-up duration, bone healing time, bone graft incorporation, local recurrence events, time to recurrence, and recurrence location.

Measurement methods

Imaging assessment: X-ray, CT, and MRI were used to evaluate lesion extent, cortical destruction, and soft tissue involvement. Maximum lesion diameter was defined as the largest dimension on CT or MRI across three planes. Postoperative X-rays were routinely performed at intervals to assess bone healing. Delayed union was defined as failure to meet bone healing criteria 6 months postoperatively. Local recurrence was diagnosed when imaging showed a new lesion at or adjacent to the surgical site, confirmed by repeat surgical pathology or needle biopsy if necessary.

All procedures were performed by the same team of experienced orthopedic surgeons. After standard preparation and draping, patients were positioned appropriately, and an incision was made to expose the lesion fully.

For the combined group, a cortical window was created at the lesion site. *In situ* ablation was performed using a microwave ablation system (AngioDynamics, Solero MTA System) at 50 W for 5 minutes. The ablation zone was designed to cover the entire lesion with a 1-cm margin of unaffected bone. Temperature was continuously monitored during ablation to ensure effectiveness. Thorough curettage was performed after ablation; a high-speed burr (Stryker, CORE High-Speed Drill) was used to treat residual tumor and cavity walls if needed. For the control group, a cortical window was created, followed by thorough curettage with curettes until normal bone was visualized. High-speed burring was added if necessary. In both groups, the cavity was thoroughly irrigated, and careful hemostasis was achieved. Defect reconstruction was individualized based on cavity size, location, and weight-bearing requirements, with options including bone cement filling alone, autograft/allograft bone grafting, or combined cement and bone graft reconstruction. Internal fixation with plates, screws, or intramedullary nails was added based on lesion location and skeletal stability. A drain was placed before layered closure.

Functional assessment: Limb function was evaluated preoperatively and postoperatively using the Musculoskeletal Tumor Society body of knowledge (MSTS) scoring system [15]. This system assesses six domains: pain, function, emotional acceptance, support use, walking ability, and gait. Each domain is scored 0-5, with a total score of 0-30; higher scores indicate better function. Evaluations were performed preoperatively and at 3, 6, and 12 months postoperatively, as well as at final follow-up. An MSTS score ≥24 at final follow-up was defined as excellent or good functional outcome. Improvement from baseline was calculated as the difference between postoperative and preoperative scores at each time point.

Outcome measures

Primary outcomes: (1) Local recurrence rate (proportion of patients with local recurrence during follow-up); (2) recurrence-free survival (time from surgery to first local recurrence or last follow-up). Secondary outcomes: (1) Limb function (MSTS scores at each postoperative time point, improvement from baseline, and proportion of patients with excellent/good functional outcome at final follow-up); (2) Bone healing (healing time, delayed union rate, and bone graft incorporation rate); (3) Perioperative indices (operative time and intraoperative blood loss); (4) Postoperative recovery (drainage volume, duration of drain placement, time to first ambulation, and postoperative hospital stay); (5) Complications (wound infection, delayed wound healing, and DVT).

Statistical analysis

Data were analyzed using R software (4.5.1) and SPSS software (27.0). Normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were first assessed for continuous variables. Normally distributed data with equal variances were expressed as mean ± standard deviation and compared using independent-samples t-tests. Non-normally distributed data were expressed as median [interquartile range] and compared using Mann-Whitney U tests. Categorical variables were expressed as counts (percentages) and compared using chi-square test or Fisher's exact test. Recurrence-free survival was compared using Kaplan-Meier curves and log-rank tests, with HR and 95% CI calculated. Cox proportional hazards regression was used to identify factors associated with local recurrence. Variables with $P<0.05$ in univariable analysis or clinical significance were included in multivariable analysis. Chi-square tests for trend were used to assess dose-response relationships between cumulative risk factor count and recurrence risk. Interaction tests were performed to determine whether the effect of surgical approach varied by risk stratification. Subgroup analyses were conducted based on pathologic type (GCTB vs. non-GCTB<3 cm vs. 3-6 cm vs. >6 cm), and risk stratification (low-risk: 0-1 factors; high-risk: ≥2 factors). All tests were two-sided, and $P<0.05$ was considered significant.

Results

Baseline characteristics

No significant differences were observed between the two groups in age distribution (P=

0.653), sex (P=0.508), BMI (P=0.349), pathologic tumor type (P=0.761), lesion location (P=0.731), periarticular knee location (P=0.403), maximum lesion diameter distribution (P=0.536), cortical destruction (P=0.467), extensive cortical destruction (P=0.428), soft tissue involvement (P=0.436), preoperative pathologic fracture (P=0.631), diabetes mellitus (P=0.788), hypertension (P=0.555), or ASA classification (P=0.643). These findings indicate that baseline characteristics were comparable between groups (**Table 1**).

Perioperative parameters

Operative time was significantly longer in the combined group than in the control group (P<0.001). No significant differences were found in intraoperative blood loss (P=0.550), defect reconstruction method (P=0.512), or use of internal fixation (P=0.390) (**Table 2**).

Postoperative recovery and complications

Time to first ambulation was significantly shorter in the combined group (P=0.048). No significant differences were observed in postoperative drainage volume (P=0.287), duration of drain placement (P=0.711), postoperative hospital stay (P=0.117), wound infection (P=1.000), delayed wound healing (P=0.624), or DVT (P=1.000) (**Table 3**).

Bone healing time and quality

Follow-up duration was comparable between groups (P=0.131). Bone healing time was significantly shorter in the combined group (P<0.001), and the distribution of healing time also differed significantly (P<0.001). Delayed union occurred significantly less frequently in the combined group than in the control group (5.8% vs. 18.8%, P=0.001) (**Table 4**).

Subgroup analysis: bone healing in patients with bone graft reconstruction

Among patients who underwent bone graft reconstruction, no significant differences were found between groups in graft healing time (P=0.071), graft incorporation rate (P=0.070), or delayed union rate (P=0.070). This suggests that bone healing outcomes were similar between surgical approaches in this subgroup (**Table 5**).

Postoperative limb function (MSTS Scores)

Preoperative MSTS scores did not differ significantly between groups (P=0.289). Both groups showed progressive improvement in MSTS scores over time. The combined group achieved significantly higher scores at 3 months (P=0.006), 6 months (P<0.001), 12 months (P<0.001), and final follow-up (P<0.001) compared to the control group (**Table 6**; **Figure 1A**, **1B**). In terms of improvement from baseline, the combined group showed greater gains at all time points: 3 months (P=0.009), 6 months (P<0.001), 12 months (P<0.001), and final follow-up (P<0.001) (**Figure 1B**). The distribution of MSTS score categories at final follow-up differed significantly between groups (P<0.001) (**Figure 1C**). However, the rate of excellent or good functional outcome at final follow-up did not reach statistical significance (P=0.181) (**Figure 1D**).

Local recurrence

Local recurrence rate was lower in the combined group than in the control group (7.1% vs. 18.0%, P=0.008). Among patients who experienced recurrence, time to recurrence did not differ significantly (P=0.518). No significant differences were observed in the distribution of recurrence timing or recurrence location (**Table 6**). Kaplan-Meier analysis showed significantly higher recurrence-free survival in the combined group (log-rank P=0.007). Intralesional curettage alone was associated with a higher recurrence risk (HR=2.6, 95% CI: 1.27-5.34) (**Figure 2**).

Risk factor analysis for local recurrence

Univariate Cox regression identified surgical approach (P=0.009), maximum lesion diameter maximum lesion diameter >6 cm (P=0.008), extensive (P<0.001), and soft tissue involvement (P<0.001) as significantly associated with local recurrence. Age (P=0.983), sex (P=0.363), pathologic type (P=0.996), periarticular knee location (P=0.515), preoperative pathologic fracture (P=0.619), defect reconstruction method (P=0.973, P=0.820), internal fixation (P=0.243), diabetes mellitus (P=0.389), and hypertension (P=0.740) were not significantly associated with recurrence (**Table 7**).

Table 1. Comparison of baseline characteristics

Variable	Total	Combined group (n=156)	Control group (n=128)	Statistic	*P* value
Age				0.851	0.653
≤30 years	128 (45.07%)	67 (42.95%)	61 (47.66%)		
31-50 years	111 (39.08%)	62 (39.74%)	49 (38.28%)		
>50 years	45 (15.85%)	27 (17.31%)	18 (14.06%)		
Sex				0.438	0.508
Male	157 (55.28%)	89 (57.05%)	68 (53.12%)		
Female	127 (44.72%)	67 (42.95%)	60 (46.88%)		
BMI				0.877	0.349
≥25 kg/m^2	51 (17.96%)	25 (16.03%)	26 (20.31%)		
<25 kg/m^2	233 (82.04%)	131 (83.97%)	102 (79.69%)		
Pathologic tumor type				1.169	0.761
Giant cell tumor of bone	137 (48.24%)	78 (50.00%)	59 (46.09%)		
Aneurysmal bone cyst	55 (19.37%)	28 (17.95%)	27 (21.09%)		
Chondroblastoma	30 (10.56%)	18 (11.54%)	12 (9.38%)		
Others	62 (21.83%)	32 (20.51%)	30 (23.44%)		
Lesion location				1.294	0.731
Distal femur	90 (31.69%)	52 (33.33%)	38 (29.69%)		
Proximal tibia	73 (25.70%)	41 (26.28%)	32 (25.00%)		
Distal radius	48 (16.90%)	23 (14.74%)	25 (19.53%)		
Others	73 (25.70%)	40 (25.64%)	33 (25.78%)		
Periarticular knee lesion				0.698	0.403
Yes	163 (57.39%)	93 (59.62%)	70 (54.69%)		
No	121 (42.61%)	63 (40.38%)	58 (45.31%)		
Maximum lesion diameter				1.246	0.536
<3 cm	57 (20.07%)	28 (17.95%)	29 (22.66%)		
3-6 cm	161 (56.69%)	89 (57.05%)	72 (56.25%)		
>6 cm	66 (23.24%)	39 (25.00%)	27 (21.09%)		
Cortical destruction				0.530	0.467
Yes	61 (21.48%)	31 (19.87%)	30 (23.44%)		
No	223 (78.52%)	125 (80.13%)	98 (76.56%)		
Extensive cortical destruction				0.627	0.428
Yes	73 (25.70%)	43 (27.56%)	30 (23.44%)		
No	211 (74.30%)	113 (72.44%)	98 (76.56%)		
Soft tissue involvement				0.606	0.436
Yes	82 (28.87%)	48 (30.77%)	34 (26.56%)		
No	202 (71.13%)	108 (69.23%)	94 (73.44%)		
Preoperative pathologic fracture				0.231	0.631
Yes	50 (17.61%)	29 (18.59%)	21 (16.41%)		
No	234 (82.39%)	127 (81.41%)	107 (83.59%)		
Diabetes mellitus				0.072	0.788
Yes	19 (6.69%)	11 (7.05%)	8 (6.25%)		
No	265 (93.31%)	145 (92.95%)	120 (93.75%)		
Hypertension				0.348	0.555
Yes	30 (10.56%)	18 (11.54%)	12 (9.38%)		
No	254 (89.44%)	138 (88.46%)	116 (90.62%)		
ASA classification				0.215	0.643
I	180 (63.38%)	97 (62.18%)	83 (64.84%)		
II-III	104 (36.62%)	59 (37.82%)	45 (35.16%)		

Note: MSTS, Musculoskeletal Tumor Society score; BMI, body mass index; ASA, American Society of Anesthesiologists classification.

Table 2. Comparison of perioperative indices

Variable	Total	Combined group (n=156)	Control group (n=128)	Statistic	*P* value
Operative time (min)	130.00 [110.00, 152.25]	139.00 [114.75, 164.75]	121.50 [109.75, 138.00]	3.991	<0.001
Intraoperative blood loss (mL)	287.50 [213.75, 352.00]	291.50 [216.25, 351.50]	274.50 [211.50, 352.00]	0.598	0.55
Defect reconstruction method				1.341	0.512
Bone cement filling alone	154 (54.23%)	89 (57.05%)	65 (50.78%)		
Autograft/allograft bone grafting	84 (29.58%)	42 (26.92%)	42 (32.81%)		
Combined cement and bone graft	46 (16.20%)	25 (16.03%)	21 (16.41%)		
Internal fixation use				0.738	0.39
Yes	172 (60.56%)	98 (62.82%)	74 (57.81%)		
No	112 (39.44%)	58 (37.18%)	54 (42.19%)		

Table 3. Comparison of postoperative recovery and complications

Variable	Total	Combined group (n=156)	Control group (n=128)	Statistic	*P* value
Postoperative drainage volume (mL)	178.00 [133.75, 234.50]	187.50 [134.50, 247.00]	175.00 [133.50, 224.25]	1.064	0.287
Duration of drain placement (days)	3.00 [2.00, 4.00]	3.00 [2.75, 4.00]	3.00 [2.00, 4.00]	0.371	0.711
Time to first ambulation (days)	3.00 [3.00, 4.00]	3.00 [3.00, 4.00]	3.00 [2.75, 4.00]	1.974	0.048
Postoperative hospital stay (days)	9.00 [6.00, 11.00]	9.00 [7.00, 12.00]	9.00 [6.00, 11.00]	1.570	0.117
Wound infection				0.000	1.000
Yes	9 (3.17%)	5 (3.21%)	4 (3.12%)		
No	275 (96.83%)	151 (96.79%)	124 (96.88%)		
Delayed wound healing				0.240	0.624
Yes	13 (4.58%)	8 (5.13%)	5 (3.91%)		
No	271 (95.42%)	148 (94.87%)	123 (96.09%)		
Deep vein thrombosis				0.000	1.000
Yes	5 (1.76%)	3 (1.92%)	2 (1.56%)		
No	279 (98.24%)	153 (98.08%)	126 (98.44%)		

Table 4. Comparison of bone healing time and quality

Variable	Combined group (n=156)	Control group (n=128)	Statistic	*P* value
Follow-up duration (months)	33.0±11.7	31.0±10.4	t=-1.515	0.131
Bone healing time (months)	4.3±1.5	5.0±1.5	t=3.948	<0.001
Bone healing time distribution [n (%)]			χ^2=22.007	<0.001
<3 months	23 (14.7)	3 (2.3)		
3-6 months	124 (79.5)	101 (78.9)		
>6 months	9 (5.8)	24 (18.8)		
Delayed union (>6 months) [n (%)]	9 (5.8)	24 (18.8)	χ^2=10.307	0.001

Table 5. Comparison of bone healing in patients with bone graft reconstruction (subgroup analysis)

Variable	Combined group (n=67)	Control group (n=63)	Statistic	*P* value
Graft healing time (months)	4.3±1.4	4.8±1.6	t=1.819	0.071
Graft incorporation rate [n (%)]	64 (95.5)	54 (85.7)	Fisher	0.07
Delayed union [n (%)]	3 (4.5)	9 (14.3)	Fisher	0.07

On multivariate Cox regression, surgical approach (P<0.001), soft tissue involvement (P< 0.001), maximum lesion diameter >6 cm (P< 0.001), and extensive cortical destruction (P< 0.001) remained as independent predictors of local recurrence. MWA combined with curettage significantly reduced recurrence risk, while soft tissue involvement, larger lesion size, and extensive cortical destruction increased recurrence risk. Preoperative pathologic fracture was not an independent predictor by the multivariable model (P=0.863) (**Table 8**).

Table 6. Comparison of local recurrence

Variable	Combined group (n=156)	Control group (n=128)	Statistic	*P* value
Local recurrence [n (%)]	11 (7.1)	23 (18.0)	χ^2=6.950	0.007
Time to recurrence (months, M [IQR])	14.0 [10.5-23.0]	18.0 [14.0-21.0]	Z=0.646	0.518
Recurrence timing distribution [n (%)]			-	
≤12 months	4 (36.4)	3 (13.0)		
13-24 months	5 (45.5)	18 (78.3)		
>24 months	2 (18.2)	2 (8.7)		
Recurrence location [n (%)]			-	
In situ recurrence	9 (83.3)	20 (86.4)		
Surrounding soft tissue recurrence	2 (16.7)	3 (13.6)		

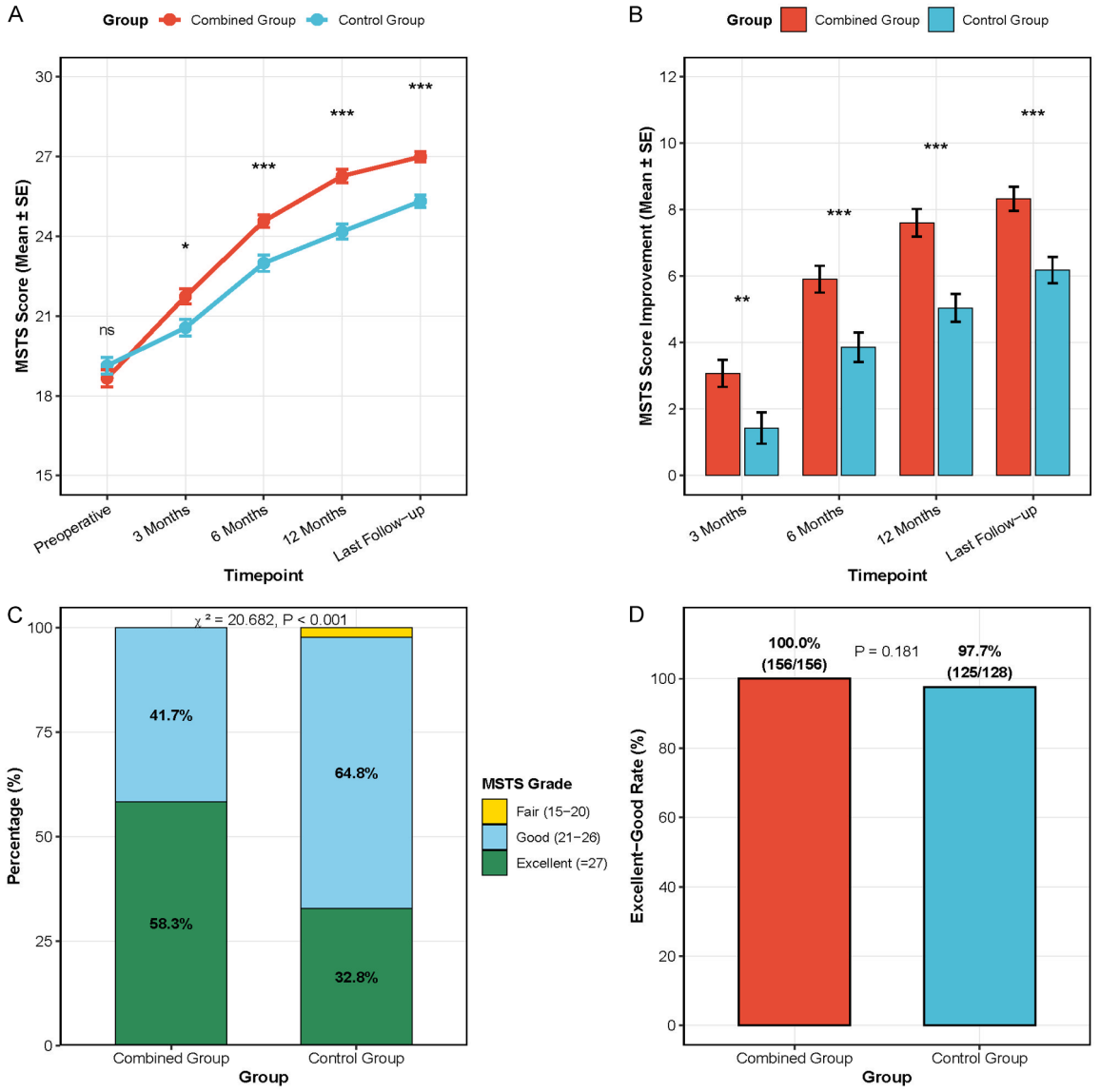

Figure 1. Trends in MSTS scores and functional outcomes at final follow-up. A: Trends in MSTS scores at different time points in both groups. B: Comparison of MSTS scores at different postoperative time points between the two groups. C: Distribution of MSTS score categories at final follow-up. D: Comparison of rate of excellent or good functional outcome at final follow-up. Note: MSTS, Musculoskeletal Tumor Society score; SE, standard error. ns, not significant; *P<0.05; **P<0.01; ***P<0.001.

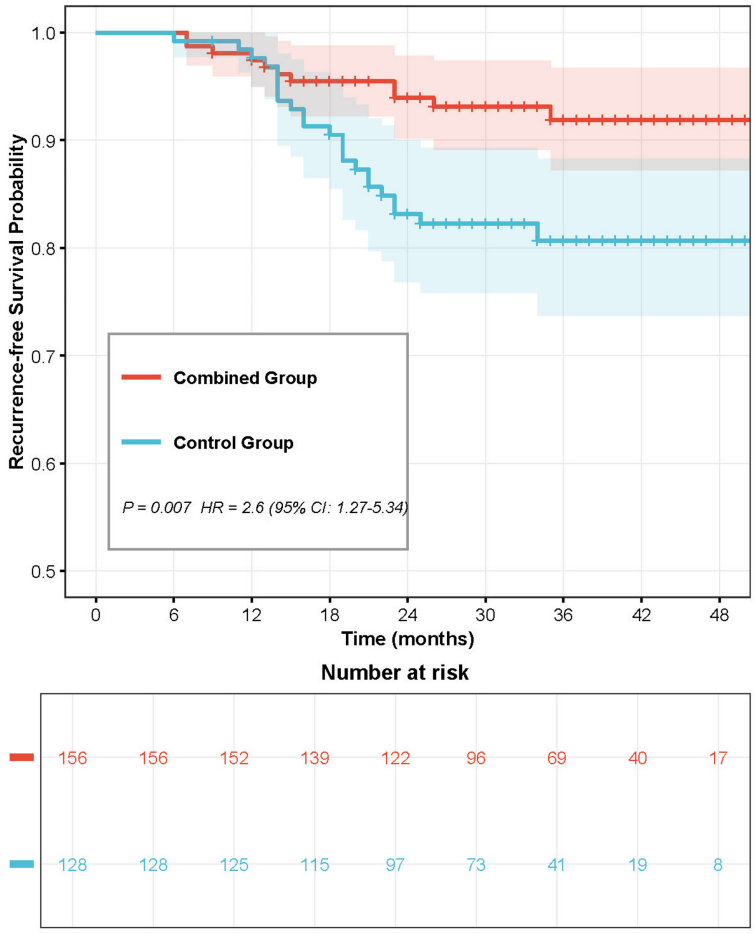

Figure 2. Kaplan-Meier curves comparing recurrence-free survival. Note: HR, hazard ratio; CI, confidence interval.

Subgroup analysis by pathological type

In the GCTB subgroup, local recurrence rates did not differ significantly between groups (P= 0.387). However, the combined group had significantly better final follow-up MSTS scores (P<0.001) and shorter bone healing time (P= 0.003). In the non-GCTB subgroup, the combined group showed significantly lower recurrence rates (P=0.006), higher final follow-up MSTS scores (P<0.001), and shorter healing time (P=0.009) (**Table 9**).

Subgroup analysis by lesion size

For lesions <3 cm, local recurrence rate (P= 0.612) and bone healing time (P=0.771) did not differ between groups, but final follow-up MSTS scores were higher in the combined group (P= 0.004). For lesions 3-6 cm, the combined group had better MSTS scores (P<0.001) and shorter healing time (P<0.001), while recurrence rates did not differ significantly (P= 0.140). For lesions >6 cm, the combined group had significantly lower re-currence rates (P=0.021) and better MSTS scores (P=0.003), while healing time was similar (P=0.088) (**Table 10**).

Cumulative risk factor analysis and risk stratification

Using soft tissue involvement, maximum lesion diameter >6 cm, and extensive cortical destruction as risk factors, we observed a progressive increase in recurrence risk with the number of risk factors present (P<0.001) (**Figure 3A**). Kaplan-Meier analysis stratified by risk level (low-risk: 0-1 factors; high-risk: ≥2 factors) showed significant differences between surgical approaches in both strata. In the low-risk group, recurrence-free survival differed between approaches (P=0.040, HR=3.12, 95% CI: 0.99-9.80). In the high-risk group, the difference was also significant (P=0.008, HR=3.37, 95% CI: 1.31-8.69) (**Figure 3B**). Interaction testing showed no significant interaction between surgical approach and risk stratification (P=0.786) (**Figure 3B**).

Discussion

This study evaluated the clinical efficacy of MWA combined with intralesional curettage versus curettage alone for limb salvage in locally aggressive benign bone tumors, with comprehensive assessment of oncological control, postoperative limb function recovery, and bone healing outcomes. The results confirmed that adjunctive MWA conferred distinct clinical benefits over isolated curettage, including reduced local recurrence, superior functional restoration, and accelerated bone repair. These findings provide high-level clinical evidence to support the use of MWA as a reliable local adjuvant strategy, and are consistent with contemporary treatment principles that prioritize radical tumor control while maximizing limb function preservation [4, 5].

Table 7. Univariable Cox regression analysis of factors associated with local recurrence

Variable	HR	95% CI	*P* value
Surgical approach			
Curettage alone (reference)	1	-	-
Microwave combined with curettage	0.38	0.19-0.79	0.009
Age			
≤30 years (reference)	1	-	-
>30 years	1.01	0.51-1.98	0.983
Sex			
Male (reference)	1	-	-
Female	1.37	0.70-2.68	0.363
Pathological type			
Giant cell tumor of bone (reference)	1	-	-
Other types	1	0.51-1.96	0.996
Maximum lesion diameter			
<3 cm (reference)	1	-	-
3-6 cm	1.76	0.51-6.08	0.372
>6 cm	5.28	1.54-18.12	0.008
Periarticular knee lesion			
No (reference)	1	-	-
Yes	0.8	0.41-1.57	0.515
Extensive cortical destruction			
No (reference)	1	-	-
Yes	3.99	2.03-7.86	<0.001
Soft tissue involvement			
No (reference)	1	-	-
Yes	5.37	2.65-10.86	<0.001
Preoperative pathologic fracture			
No (reference)	1	-	-
Yes	0.79	0.30-2.03	0.619
Defect reconstruction method			
Bone cement (reference)	1	-	-
Bone grafting	1.01	0.47-2.20	0.973
Combined reconstruction	1.11	0.44-2.80	0.82
Internal fixation use			
No (reference)	1	-	-
Yes	1.55	0.74-3.25	0.243
Diabetes mellitus			
No (reference)	1	-	-
Yes	0.42	0.06-3.05	0.389
Hypertension			
No (reference)	1	-	-
Yes	1.19	0.42-3.39	0.74

Note: HR, hazard ratio; CI, confidence interval.

Intralesional curettage remains the mainstream limb-sparing procedure for locally aggressive benign bone tumors, as it preserves native bone anatomy and joint integrity to maintain limb mechanical function and avoid the functional impairment caused by extensive resections on mobility [5]. Nevertheless, inherent limitations persist with curettage alone. Irregular and infiltrative tumor margins, particularly in Campanacci grade III lesions or cases with soft tissue extension, make complete clearance of microscopic tumor residuals along the osseous cavity wall difficult, even with routine high-speed burring. Local recurrence originates predominantly from undetectable microscopic tumor remnants rather than macroscopic residual lesions [6], and insufficient intraoperative local management further elevates recurrence risk in high-risk cases.

The superior local tumor control achieved by combined MWA and curettage can be attributed to the thermal ablation mechanism of MWA. Microwave electromagnetic energy induces rapid tissue hyperthermia, resulting in irreversible coagulative necrosis of tumor cells and diminishing cell viability prior to and during curettage. Jiang et al. [16] demonstrated that MWA followed by bone defect reconstruction achieved favorable mid-term oncological outcomes in GCTB, with no case of in situ recurrence. Accumulated evidence from systematic reviews also indicates that thermal ablation adjuvant regimens represented by MWA yield a low pooled recurrence rate of 0-10% [12]. Compared to traditional chemical ablation and cryotherapy, MWA allows precise regulation of energy output, ablation scope and duration, enabling effective coverage of irregular tumor cavities and anatomic areas inaccessible to conventional curettage instruments [7, 8]. Multivariate regression in

Table 8. Multivariate Cox regression analysis of factors associated with local recurrence

Variable	β	SE	Wald	HR	95% CI	*P* value
Surgical approach (microwave combined vs. curettage alone)	-1.367	0.377	13.118	0.25	0.12-0.53	<0.001
Soft tissue involvement (yes vs. no)	1.882	0.366	26.501	6.57	3.21-13.44	<0.001
Maximum lesion diameter >6 cm (vs. ≤6 cm)	1.214	0.353	11.803	3.37	1.68-6.73	<0.001
Extensive cortical destruction (yes vs. no)	1.528	0.368	17.268	4.61	2.24-9.47	<0.001
Preoperative pathologic fracture (yes vs. no)	0.088	0.512	0.03	1.09	0.40-2.98	0.863

Note: HR, hazard ratio; CI, confidence interval; SE, standard error.

Table 9. Comparison of treatment outcomes between surgical approaches according to pathological type (subgroup analysis)

Pathologic type	Variable	Combined group	Control group	*P* value
Giant cell tumor of bone	n	78	59	-
	Recurrence rate [n (%)]	7 (9.0)	9 (15.3)	0.387
	Final MSTS score (points)	27.1±2.6	25.3±3.0	<0.001
	Bone healing time (months)	4.3±1.6	5.2±1.6	0.003
Non-GCTB tumors	n	78	69	-
	Recurrence rate [n (%)]	4 (5.1)	14 (20.3)	0.006
	Final MSTS score (points)	26.9±2.3	25.4±2.4	<0.001
	Bone healing time (months)	4.2±1.5	4.9±1.5	0.009

Note: MSTS, Musculoskeletal Tumor Society score; GCTB, Giant cell tumor of bone.

Table 10. Comparison of treatment outcomes between surgical approaches according to lesion size (subgroup analysis)

Lesion size	Variable	Combined group	Control group	*P* value
<3 cm	n	30	29	-
	Recurrence rate [n (%)]	1 (3.3)	2 (6.9)	0.612
	Final MSTS score (points)	27.2±2.5	25.3±2.4	0.004
	Bone healing time (months)	4.8±1.3	4.9±1.3	0.771
3-6 cm	n	87	72	-
	Recurrence rate [n (%)]	5 (5.7)	10 (13.9)	0.14
	Final MSTS score (points)	26.9±2.6	25.3±2.9	<0.001
	Bone healing time (months)	4.2±1.4	5.1±1.6	<0.001
>6 cm	n	39	27	-
	Recurrence rate [n (%)]	5 (12.8)	11 (40.7)	0.021
	Final MSTS score (points)	27.2±2.3	25.3±2.4	0.003
	Bone healing time (months)	4.1±1.8	4.8±1.6	0.088

Note: MSTS, Musculoskeletal Tumor Society score.

our cohort further verified that surgical modality was an independent protective factor against recurrence. Consistent with previous studies focusing on high-risk GCTB patients receiving preoperative denosumab [11, 17], MWA-assisted curettage effectively lowered recurrence risk and facilitated joint preservation, confirming the stable protective effect of MWA independent of tumor staging and anatomic location.

Beyond oncological control, long-term limb function preservation is a core therapeutic goal for this patient population. Concerns have been raised that adjuvant thermal ablation may injure periarticular healthy tissues and compromise joint function or bone healing. Our data demonstrated that patients in the combined group achieved significantly higher MSTS scores and greater functional improvement at all postoperative follow-up time points, consistent

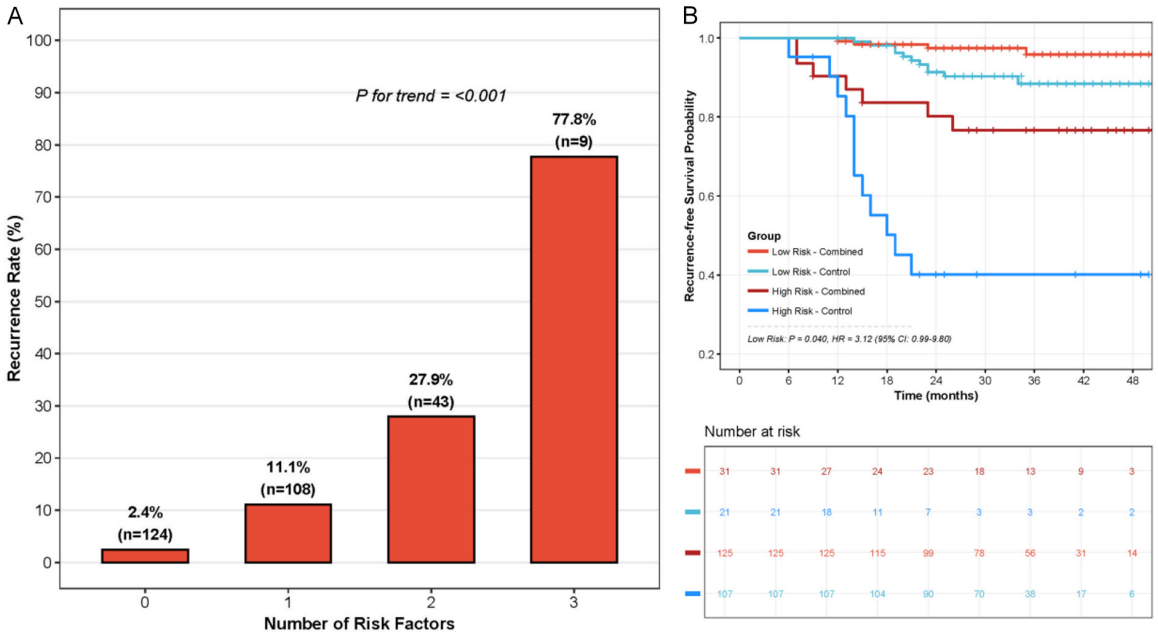

Figure 3. Cumulative risk factor analysis and risk-stratified recurrence-free survival. A: Local recurrence risk according to number of risk factors present (trend test). B: Kaplan-Meier curves comparing recurrence-free survival by surgical approach, stratified by risk level (low-risk vs. high-risk). Numbers at risk are shown below the curves. Note: HR, hazard ratio; CI, confidence interval.

with previous case series reporting satisfactory functional recovery after MWA-assisted bone tumor surgery [18]. The functional advantages of combined therapy are multifactorial: optimized local control reduces the need for secondary surgery and avoids cumulative soft tissue and joint damage from repeated interventions; MWA achieves radical local tumor eradication without expanding surgical resection margins, thereby maintaining periarticular bone stability and structural integrity; additionally, the reduced recurrence anxiety improves patient rehabilitation compliance and early weight-bearing training. Of note, although the combined group exhibited better overall functional scores, the proportion of excellent and good functional outcomes at final follow-up showed no statistical intergroup difference. This implies that the benefits of MWA are mainly reflected in faster functional recovery and improved average MSTS performance, rather than further elevating the long-term optimal functional attainment rate. Long-term limb function in GCTB is largely determined by baseline joint condition, cartilage integrity and lesion anatomic site [19], which should be fully communicated to patients for rational management of preoperative expectations.

Bone healing and reconstruction efficacy are critical determinants of limb-salvage success. Post-curettage bone defects are commonly reconstructed with bone cement, autologous/allogeneic bone grafts, or combined materials, with varied performance in early mechanical stability, long-term bone remodeling and recurrence surveillance. Theoretically, microwave thermal diffusion may impair perilesional blood perfusion and hinder bone repair; conversely, MWA eliminates residual tumor activity and stabilizes the local biological microenvironment, creating favorable conditions for bone matrix remodeling and healing. In the present study, the combined group presented a shorter bone healing time and a lower delayed union rate, confirming the overall favorable effect of MWA on bone repair. Conventional adjuvants such as high-speed burring and bone cement filling have been proven to reduce recurrence, whereas chemical adjuvants yield inconsistent healing outcomes [20]. Our subgroup analysis further showed no significant intergroup differences in graft healing time, graft incorporation rate and delayed union rate among patients receiving bone graft reconstruction, suggesting that the healing benefit of MWA may be modulated by reconstruction modality. Bone graft integration relies heavily on revascularization,

mechanical stability and surrounding microenvironment, and the potential long-term benefits of MWA may require extended follow-up to be fully validated.

Safety is a prerequisite for clinical promotion of energy-based ablation techniques. Excessive thermal diffusion of MWA may cause soft tissue burn, neurovascular injury and subchondral bone damage near joints. However, our study showed that the incidence of postoperative complications was comparable between the two groups, indicating that standardized MWA operation does not increase overall procedural risk. *Ex vivo* research has confirmed that the efficacy and safety margin of thermal ablation depend largely on precise energy field regulation and distance control [21]. Accurate probe placement, real-time intraoperative temperature monitoring and periarticular protective measures are therefore essential to ensure procedural safety, a principle shared by both MWA and cryotherapy despite different ablation mechanisms.

Our study identified soft tissue involvement, lesion diameter >6 cm, and extensive cortical destruction as independent risk factors for local recurrence, which is in line with previous imaging and clinical investigations [22, 23]. Tumor-joint distance, cortical destruction pattern and overall tumor burden are closely correlated with recurrence propensity across different anatomic sites and pathological types [22, 23]. Moreover, once soft tissue recurrence occurs, it tends to present an intractable recurrent tendency [24]. These findings support incorporating the three above-mentioned risk factors into preoperative risk stratification, and recommend intensified local adjuvant intervention with MWA in high-risk subgroups.

Surgical excision remains the mainstream curative modality for GCTB, while denosumab serves as a complementary systemic therapy for selected patients. Although preoperative denosumab can reduce tumor volume and facilitate joint preservation, its effect on long-term recurrence remains controversial and is susceptible to selection bias [19]. Current randomized controlled trials also fail to confirm a definite recurrence-free survival benefit of preoperative denosumab [25], highlighting the irreplaceable value of optimizing local adjuvant ablation strategies.

Strengths of this study include a relatively large sample size, well-balanced baseline characteristics, and simultaneous evaluation of oncological, functional and bone healing endpoints. Multivariate regression, pathologic and lesion-size subgroup analyses, as well as cumulative risk stratification further enhance its clinical reference value, and the inclusion of multiple pathologic subtypes and periarticular lesions strengthens the external applicability. As a retrospective cohort study, inherent limitations included unavoidable selection bias and unmeasured confounding factors such as surgeon operative habit, curettage thoroughness and patient rehabilitation compliance. Statistical power was limited in certain small subgroups, and variations in reconstruction, internal fixation strategies and individual lesion morphology may also have interfered with outcome assessment. In addition, the follow-up duration was insufficient to evaluate late recurrence and long-term joint function prognosis. Well-designed prospective controlled trials with prolonged follow-up are warranted to further validate our conclusions.

Conclusion

The MWA plus intralesional curettage for locally aggressive benign bone tumors demonstrated a more reliable local tumor control, better postoperative limb function recovery, and more favorable bone healing without an increased risk for major complications. Soft tissue involvement, large lesion volume, and more extensive cortical destruction are strongly linked to recurrence risk. The assessment of cumulative risk can guide the surgical decision-making process and follow-up.

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Disclosure of conflict of interest

None.

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