

Supplementary Materials

Robotic-assisted navigation improves procedural precision, efficiency, and safety in CT-guided pulmonary nodule microwave ablation

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1 **Supplementary Table 1. Outcomes of robotic versus freehand before PSM**

Variable	Total (<i>n</i> = 183)	Robotic group (<i>n</i> = 130)	Freehand group (<i>n</i> = 53)	<i>P</i> value
Deviation (mm), M (Q ₁ , Q ₃)	4 (2, 6)	3.0 (2, 5)	6 (5, 10)	< 0.01
Adjustments, M (Q ₁ , Q ₃)	2 (2, 3.0)	2 (1, 2)	4 (3, 4)	< 0.01
Number of CT scans, M (Q ₁ , Q ₃)	2 (2, 4)	2 (1, 2)	6 (5, 7)	< 0.01
Complication, <i>n</i> (%)				< 0.01
Occur	108 (59.02)	65 (50.00)	43 (81.13)	
None	75 (40.98)	65 (50.00)	10 (18.87)	
Pneumothorax, <i>n</i> (%)				< 0.01
Occur	74 (40.44)	39 (30.00)	35 (66.04)	
None	109 (59.56)	91 (70.00)	18 (33.96)	
Chest drain insertion, <i>n</i> (%)				< 0.01
Occur	19 (10.38)	8 (6.15)	11 (20.75)	
None	164 (89.62)	122 (93.85)	42 (79.25)	
Hemorrhage, <i>n</i> (%)				0.86
Occur	36 (19.67)	26 (20.00)	10 (18.87)	
None	147 (80.33)	104 (80.00)	43 (81.13)	

3 **Supplementary Table 2. Subgroup analyses of deviation and adjustments: between-group**
4 **subgroup comparisons**

Distance	Variable	Robotic	Robotic	Freehand	Freehand	95%CI	P value
		group	M (Q1,	group	M (Q1,		
		(n)	Q3)	(n)	Q3)		
≤ 80 mm	Deviation (mm)	70	3.00	27	7.00	-3.00 (-	< 0.001
			(2.00,		(5.00,	4.00, -	
	Adjustments	70	5.00)	27	10.00)	3.00)	< 0.001
			2.00		3.00	-1.00 (-	
> 80 mm	Deviation (mm)	60	(1.00,	26	(2.00,	1.00, -	< 0.001
			3.00)		4.00)	1.00)	
	Adjustments	60	3.00	26	6.00	-3.00 (-	< 0.001
			(2.00,		(4.25,	3.00, -	
			5.00)		8.50)	3.00)	
			2.00		4.00	-2.00 (-	
			(1.00,		(3.00,	2.00, -	
			2.00)		4.00)	2.00)	
Lobe	Variable	Robotic	Robotic	Freehand	Freehand	95%CI	P value
		group	M (Q1,	group	M (Q1,		
		(n)	Q3)	(n)	Q3)		
Upper lobe	Deviation	70	2.50	38	6.50	-4.00 (-	< 0.001
			(2.00,		(5.00,	4.00, -	
	Adjustments	70	4.75)	38	10.00)	4.00)	< 0.001
			2.00		4.00	-2.00 (-	
			(1.00,		(3.00,	2.00, -	
			2.00)		4.00)	2.00)	

Middle/lower lobes	Deviation	60	4.00	15	6.00	-2.00 (-	< 0.001
			(2.75, 5.00)		(4.50, 7.00)	2.00, - 2.00)	
	Adjustments	60	2.00	15	3.00	-1.00 (-	< 0.001
			(1.00, 3.00)		(2.50, 4.00)	1.00, - 1.00)	

Diameter	Variable	Robotic (n)	Robotic (Q1, Q3)	Freehand (n)	Freehand M (Q1, Q3)	95%CI	P value
≤ 1.0cm	Deviation	60	4.00	14	6.00	-3.00 (-	< 0.001
			(2.00, 5.00)		(5.25, 8.50)	3.00, - 2.00)	
	Adjustments	60	2.00	14	4.00	-2.00 (-	< 0.001
			(1.00, 2.00)		(3.00, 4.00)	2.00, - 2.00)	
> 1.0 cm	Deviation	70	3.00	39	7.00	-3.50 (-	< 0.001
			(2.00, 5.00)		(4.50, 10.00)	4.00, - 3.00)	
	Adjustments	70	2.00	39	3.00	-2.00 (-	< 0.001
			(1.00, 2.75)		(2.00, 4.00)	2.00, - 1.00)	

6 **Supplementary Table 3. Subgroup analyses of deviation and adjustments within robotic group**

Variable	Subgroup	N	Deviation	Adjustments	Difference in Deviation (95%CI)*		P value	Difference in Adjustments (95%CI)*		P value
Lobe	Middle/low	60	4.00 (2.75, 5.00)	2.00 (1.00, 3.00)	Reference			Reference		
	Upper	70	2.50 (2.00, 4.75)	2.00 (1.00, 2.00)	-1.00 (-1.00, 1.00)		0.029	0.00 (0.00, 0.00)		0.219
Diameter	>1.0 cm	70	3.00 (2.00, 5.00)	2.00 (1.00, 2.75)	Reference			Reference		
	≤1.0 cm	60	4.00 (2.00, 5.00)	2.00 (1.00, 2.00)	0.00 (0.00, 1.00)		0.179	0.00 (0.00, 0.00)		0.781
Distance	>80 mm	60	3.00 (2.00, 5.00)	2.00 (1.00, 2.00)	Reference			Reference		
	≤80 mm	70	3.00 (2.00, 5.00)	2.00 (1.00, 3.00)	0.00 (0.00, 0.00)		0.842	0.00 (0.00, 0.00)		0.191

7 *Difference (95%CI) is calculated as the second subgroup minus the first (reference) subgroup within
8 each variable, based on Hodges-Lehmann estimation for independent two-sample comparisons.

Supplementary Table 4. Interaction P values for subgroup analyses in full cohort

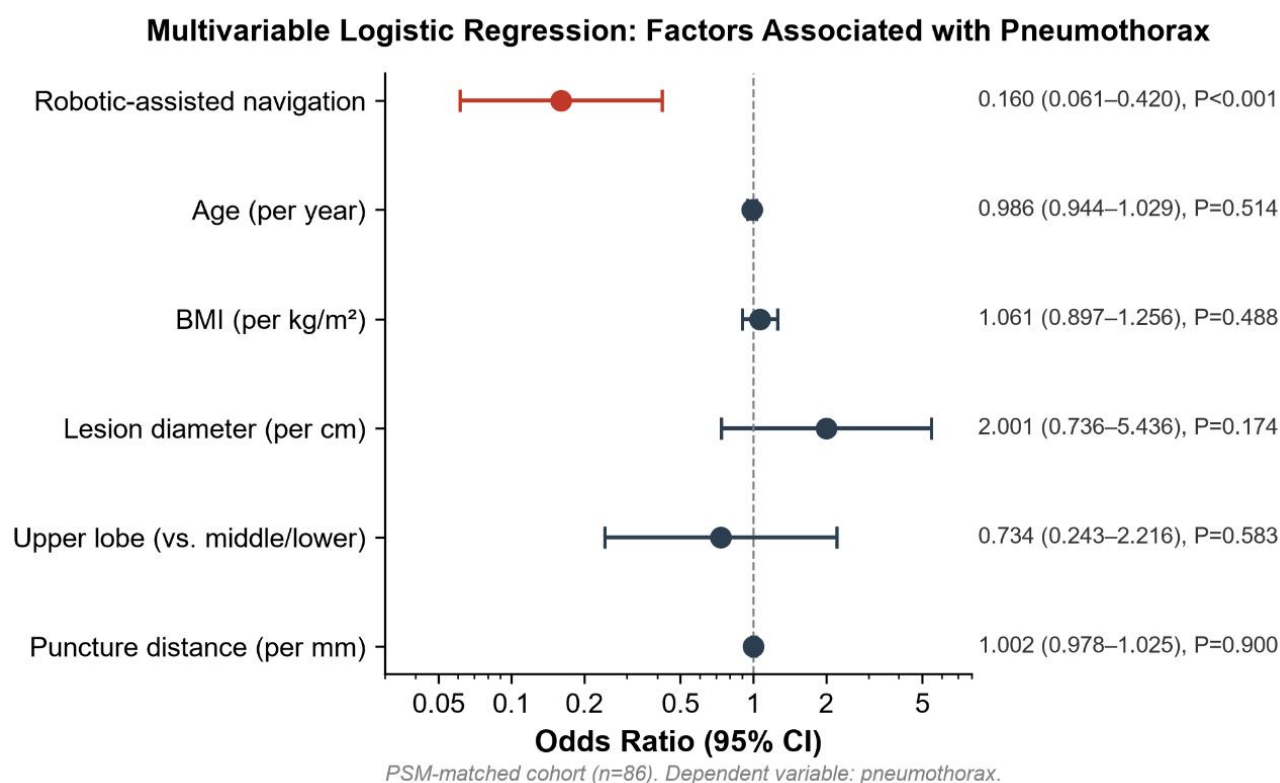
Subgroup factor	Strata	Puncture deviation (<i>P</i> for interaction)	Needle adjustments (<i>P</i> for interaction)
Puncture distance	≤80 mm vs. >80 mm	0.745	0.135
Lesion diameter	≤1.0 cm vs. >1.0 cm	0.866	0.662
Pulmonary lobe	Upper vs. middle/lower	0.112	0.147

Interaction *P* values were derived from linear regression models with a group × subgroup interaction term in the full pre-matching cohort (*n* = 183). Puncture deviation was log-transformed to address skewness. All interaction *P* values > 0.05, indicating no significant effect modification across subgroups.

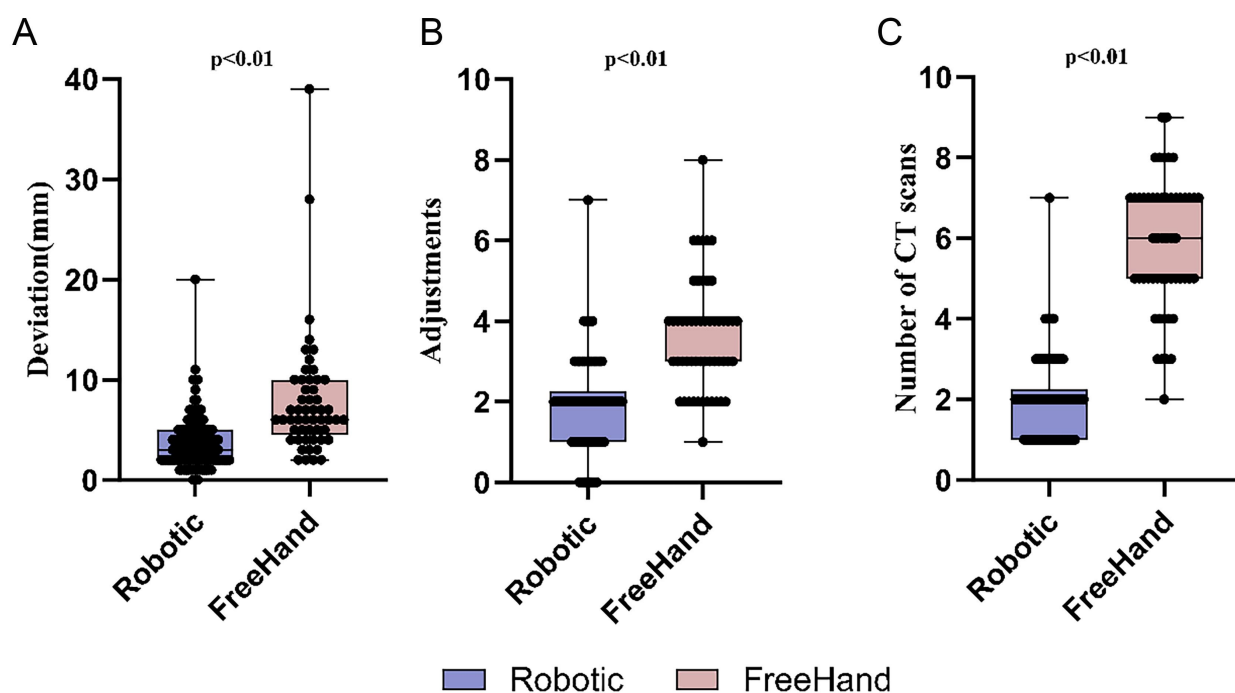
Supplementary Table 5. Interaction P values for subgroup analyses in matched cohort

Subgroup factor	Strata	Puncture deviation (<i>P</i> for interaction)	Needle adjustments (<i>P</i> for interaction)
Puncture distance	≤ 80 mm vs. > 80 mm	0.481	0.467
Lesion diameter	≤ 1.0 cm vs. > 1.0 cm	0.884	0.155
Pulmonary lobe	Upper vs. middle/lower	0.334	0.327

Interaction *P* values were derived from linear regression models with a group × subgroup interaction term in the propensity score-matched cohort (*n* = 86). Puncture deviation was log-transformed to address skewness. All interaction *P* values > 0.05, indicating no significant effect modification across subgroups.

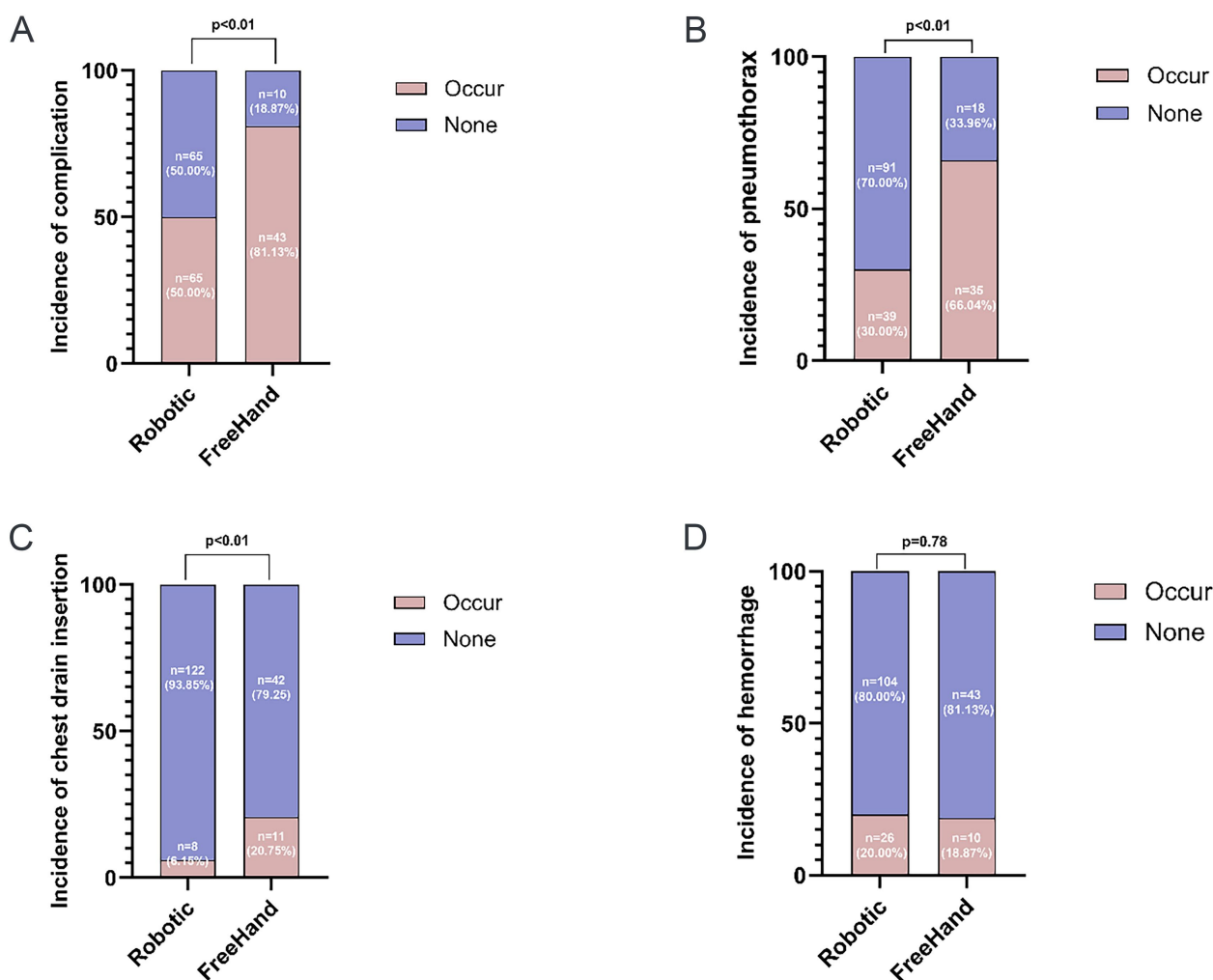


Supplementary Figure 1. Multivariate forestplot after PSM.



Supplementary Figure 2. Efficiency comparison of robotic-assisted versus freehand puncture for CT-guided microwave ablation before PSM. (A) Puncture deviation; (B) Number of CT scans; (C)

Number of needle adjustments. Data are presented as medians with interquartile ranges (IQR). *P* values were calculated using the Mann-Whitney U test. The scatter plots (or bar graphs) represent individual values or summary statistics as indicated.



Supplementary Figure 3. Complication incidence. Comparison of procedure-related complications between the robotic group and the freehand group before PSM. (A) Overall complications; (B) pneumothorax; (C) chest drain insertion; and (D) hemorrhage. Data are presented as incidence rates (%). *P* values were calculated using the χ^2 test or Fisher's exact test, as appropriate.