



OPEN Prenatal characteristics and prognosis of congenital pulmonary airway malformation: a retrospective multicenter cohort study

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Objective This study evaluated the impact of prenatal characteristics of congenital pulmonary airway malformation (CPAM) on postnatal outcomes, and investigated management strategies and outcomes in surgical versus non-surgical cases. This retrospective multicenter cohort study included 145 cases of CPAM diagnosed by prenatal ultrasound between January 2019 and May 2024. The cohort was stratified into two groups based on prenatal cystic volume ratio (CVR): CVR < 1.6 ($n = 131$) and CVR ≥ 1.6 ($n = 14$) for comparative analysis. Live-born infants were further categorized into surgical ($n = 40$) and non-surgical ($n = 89$) groups according to treatment methods. Statistical analyses included chi-square tests, t-tests, logistic regression, and Cox proportional hazards models. Univariate analysis revealed that the prevalence of prenatal large cystic lesions (macroscopic ≥ 0.5 cm), prenatal mediastinal shift, and prenatal pleural effusion/ascites were significantly higher in the CVR ≥ 1.6 group compared to the CVR < 1.6 group (all $P < 0.05$). The proportion of cases with prenatal CVR ≥ 1.6 combined with prenatal mediastinal shift was significantly greater in the surgical group than in the non-surgical group ($P < 0.05$). However, multivariate regression analysis demonstrated that after incorporating postnatal variables, prenatal variables (including CVR) were not independent factors influencing surgical intervention. Only postnatal respiratory symptoms were independently associated with the decision for surgical intervention ($P < 0.05$). Additionally, 95% of surgical procedures were performed within 20 months of birth. Postnatal respiratory symptoms are the primary clinical determinant guiding surgical intervention in infants with CPAM. Prenatal ultrasound parameters may indirectly aid in assessing the risk of surgical intervention through their potential association with postnatal symptoms. Conservative observation is safe and feasible for asymptomatic infants, whereas the onset of respiratory symptoms warrants active consideration of surgical intervention.

Keywords Congenital pulmonary airway malformation, CVR, Ultrasonography, Prenatal, Surgical procedures, Operative, Treatment outcome

Congenital pulmonary airway malformation (CPAM), formerly known as congenital cystic adenomatoid malformation (CCAM), accounts for 30–40% of all pulmonary malformations^{1,2}. This anomaly is characterized by hamartomatous proliferation resulting from disrupted lung morphogenesis, leading to abnormal growth of terminal bronchioles and the formation of cystic lesions primarily supplied by the pulmonary artery. Increased utilization of high-resolution prenatal ultrasound and widespread implementation of systematic fetal screening have significantly improved the prenatal detection rate of CPAM in recent years. Recent literature indicates an increase in the average incidence from 1/27,400 in the past to 1/7200 over the last five years³, with prenatal ultrasound diagnostic accuracy exceeding 85%².

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The prognosis of CPAM fetuses is closely related to the size of the lesion and associated complications. Although most cases exhibit a favorable prognosis, severe cases can result in complications such as mediastinal shift, pulmonary hypoplasia, polyhydramnios, or even hydrops fetalis, posing serious threats to perinatal survival⁴. Currently, postnatal management strategies for CPAM remain debated. Some experts advocate surgical intervention only when symptoms such as recurrent infections or respiratory distress are present, suggesting conservative observation for asymptomatic cases^{5,6}. Conversely, others support routine surgical resection for all cases of CPAM, irrespective of symptoms, due to concerns about infection and malignant transformation within CPAM lesions^{7,8}.

Against this backdrop, the present study undertook a retrospective multicenter cohort investigation to comprehensively examine relationships between prenatal ultrasound characteristics of CPAM, such as CPAM cystic volume ratio (CVR), mediastinal shift, and other features, and subsequent postnatal clinical presentations, surgical interventions, and overall long-term outcomes. The aim was to provide evidence for individualized risk assessment and optimization of management strategies for children with CPAM.

Methods

Patient data and study design

This retrospective multicenter cohort study collected case data from January 2019 to May 2024. Fetuses diagnosed with CPAM via prenatal ultrasound were identified at two institutions Ultrasound Medical Center, Hunan Provincial Maternal and Child Health Care Hospital, and Department of Ultrasonography, Liuyang Maternal and Child Health Care Hospital. Postpartum data were jointly collected by these two institutions in collaboration with the Department of Radiology, Hunan Children's Hospital, totaling three participating institutions.

Case recruitment and screening process

(1) Initial Screening (Prenatal Stage): A total of 165 ultrasound-confirmed CPAM fetuses were identified by the two prenatal institutions. (2) Prenatal Exclusion: Five cases were excluded (three due to intrauterine intervention and two due to maternal corticosteroid therapy), leaving 160 cases for postnatal follow-up. (3) Postnatal Follow-Up: The 160 cases underwent standardized follow-up conducted jointly by the three institutions. (4) Postnatal Exclusion: Fifteen cases were excluded due to loss to follow-up. (5) Final Inclusion: The remaining 145 eligible cases were included in the statistical analysis (Fig. 1).

Inclusion and Exclusion Criteria.

(1) Inclusion Criteria

- ① Diagnosed with CPAM via prenatal ultrasound, with complete prenatal ultrasound follow-up records and documented CPAM CVR values;
- ② Complete postnatal follow-up data.

(2) Exclusion Criteria

- ① Prenatal exclusion: Pregnant women who received intrauterine intervention or corticosteroid therapy during pregnancy;
- ② Postnatal exclusion: Absence of postnatal records in electronic medical records and unsuccessful contact after three telephone follow-up attempts at different time intervals (lost to follow-up).

Data collection and standardization procedures

Prenatal ultrasound examination

Prenatal ultrasound examinations at the two diagnosis centers (Hunan Provincial Maternal and Child Health Care Hospital, Liuyang Maternal and Child Health Care Hospital) were performed using standardized equipment (GE Voluson E8/E10 ultrasound systems) with a probe frequency of 3–8 MHz. Third-trimester ultrasound examinations followed clinical guidelines and a standardized operational protocol: (1) Preliminary screening and measurements were performed by physicians with ≥ 10 years of fetal ultrasound experience. Recorded parameters included lesion location, size, ultrasonic features, presence of pleural or abdominal effusion, associated malformations, maximum amniotic fluid depth, maternal age, and gestational age at diagnosis; (2) All ultrasound images and measurements were reviewed and confirmed by senior physicians with ≥ 20 years of clinical experience to ensure accuracy.

The maximum CPAM CVR obtained via prenatal ultrasound was used as a key study indicator. CVR was defined as the ratio of CPAM lesion volume to fetal head circumference (HC), calculated using the formula: (lesion length $\times$ width $\times$ height $\times$ 0.52)/HC. All measurements (lesion length, width, height, and HC) were recorded in centimeters (cm), with HC measured in a standard trans-thalamic transverse plane.

Prenatal ultrasound features of CPAM were classified according to Adzick's classification⁹, dividing lesions into two types: microcystic (cyst diameter < 0.5 cm) and macrocystic (cyst diameter ≥ 0.5 cm).

The Chinese Expert Consensus on the Diagnosis and Management of CPAM (2021 Version)³ explicitly recommends CVR > 1.6 as a high-risk criterion for fetal hydrops. Additionally, the 2017 Delphi International Expert Consensus by Berman et al.¹⁰, validated through deliberation by pediatric surgeons worldwide, also endorses this threshold for clinical stratification. Therefore, CPAM cases were divided into two groups based on the maximum prenatal CVR: the CVR < 1.6 group and the CVR ≥ 1.6 group.

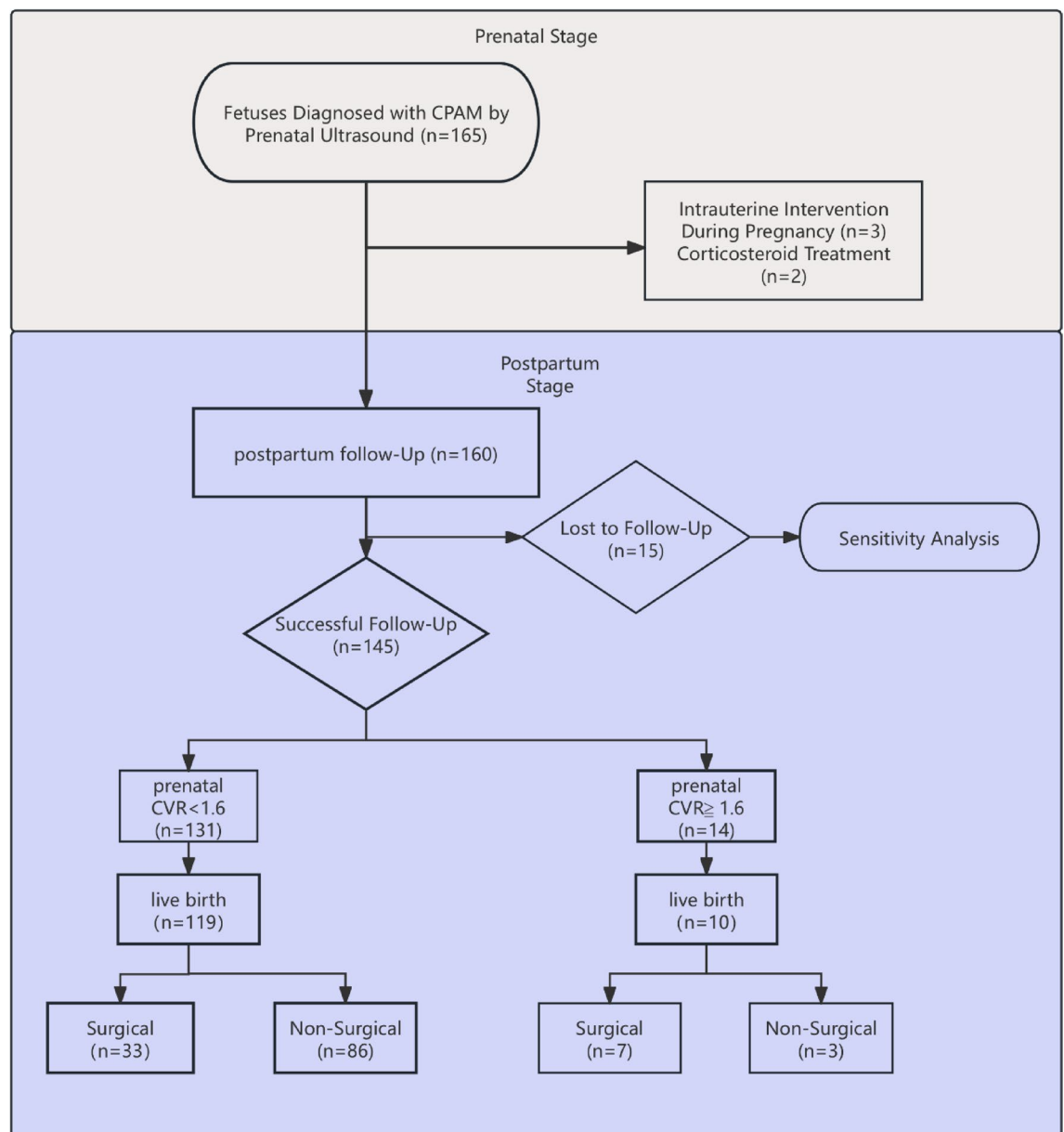


Fig. 1. Flowchart. The flowchart summarizes the study process. Initially, retrospective data on 165 fetuses diagnosed with CPAM via prenatal ultrasound were collected from two prenatal diagnosis centers. After excluding five cases (three intrauterine interventions and two maternal corticosteroid therapies), 160 entered postpartum follow-up. Subsequently, 15 cases were lost to follow-up (addressed through sensitivity analysis), and 145 cases completed follow-up. Among these, there were 129 live births, stratified based on the prenatal maximum CPAM CVR: CVR < 1.6: 119 live births (33 underwent surgery; 86 received conservative management). CVR ≥ 1.6: 10 live births (7 underwent surgery; 3 received conservative management).

Postnatal follow-up and data collection

Postnatal follow-up was conducted by three collaborating institutions according to a unified protocol. Data were systematically extracted from historical medical records using a standardized retrospective approach: (1) Postnatal records of fetuses diagnosed with CPAM via prenatal screening (January 2019 to May 2024) were retrieved from electronic medical record systems at the three institutions. (2) Methods for extracting follow-up data: ① Priority was given to reviewing regular re-examination records from electronic medical record systems, including imaging reports, outpatient records, and inpatient records. ② For cases with incomplete records, corresponding telephone follow-up records were reviewed retrospectively.

The following historical information was uniformly extracted: (1) pregnancy outcomes (termination/live birth); (2) occurrence of respiratory symptoms in surviving children. Respiratory symptoms were defined according to previous guidelines³ as dyspnea or respiratory distress, recurrent cough and wheezing, pneumothorax, or hemoptysis due to lesion compression or secondary infection; (3) treatment modality (surgical or conservative

treatment) and age at surgery; (4) CPAM lesion re-examination records, primarily using lung ultrasound, supplemented with X-ray or low-dose computed tomography (CT) as necessary. Examination timing, frequency, and lesion characteristics (size, location, boundary, and echo/density) were recorded. Postnatal follow-up for conservatively managed CPAM cases was scheduled every 3–6 months from birth until 1 year of age and every 6–12 months thereafter. Follow-up data were cross-validated for consistency.

Cases were classified as “lost to follow-up” if no postnatal data existed in the electronic medical records and contact attempts failed after at least three phone calls at different intervals. The potential impact of lost-to-follow-up cases was assessed via sensitivity analysis.

Cases were divided into surgical and non-surgical groups based on whether surgery was performed postnatally.

*Surgical indications*³

Surgery was indicated for: (1) Symptomatic children exhibiting respiratory symptoms due to lesion compression or secondary infection; (2) Asymptomatic children meeting any of the following criteria: lesion diameter greater than 2 cm (due to risk of infection and malignant transformation); lesion diameter less than 2 cm but accompanied by infection during follow-up, suspected pleuropulmonary blastoma, high malignancy risk or family history of malignancy, lung tissue or major blood vessel compression, or pneumothorax. All surgical cases were pathologically confirmed.

Ethical approval

Ethical approval was granted by the Ethics Committee of the leading institution, Hunan Provincial Maternal and Child Health Care Hospital (Approval No.: 2024003), and ethical approvals were obtained from all participating institutions. Written informed consent was secured from all participants or their legal guardians prior to inclusion of clinical, prenatal ultrasound, and postnatal follow-up data. Pregnant women acted as legal representatives for fetuses/neonates. The study protocol complies with the Declaration of Helsinki and national ethical standards for clinical research.

Statistical analysis

Data analysis was conducted using STATA version 16. Categorical variables were summarized as frequencies (n) and percentages (%) and compared between groups using the chi-square test or Fisher’s exact test. Continuous variables were presented as medians (minimum–maximum) or mean ± standard deviation (SD) and compared between groups using the t-test. Statistical significance was set at $P < 0.05$. The likelihood of surgical intervention over the follow-up period was evaluated via survival analysis (Kaplan–Meier curves with Cox regression). Factors influencing the neonatal surgical decision were assessed using logistic regression and Cox regression models. Sensitivity analyses for both approaches were performed using multiple imputation by chained equations (MICE).

Results

From January 2019 to May 2024, a total of 165 fetuses received a prenatal diagnosis of CPAM. After excluding 3 cases with intrauterine interventions, 2 cases receiving maternal corticosteroids, and 15 lost-to-follow-up cases, 145 were included in the analysis (Fig. 1).

Association between prenatal characteristics and CVR

Subjects were categorized into $CVR < 1.6$ ($n = 131$) and $CVR \geq 1.6$ ($n = 14$) groups. No significant differences existed in maternal age, gestational age at diagnosis, fetal sex, lesion location, amniotic fluid depth, or concomitant malformations ($P > 0.05$). However, significant differences were noted in lesion characteristics: the $CVR \geq 1.6$ group showed a higher prevalence of macrocystic lesions (≥ 0.5 cm; 85.7% vs. 35.9%, $P < 0.001$), mediastinal shift (92.9% vs. 40.5%, $P < 0.001$), and pleural/ascites incidence (28.6% vs. 0.8%, Fisher’s exact test, $P < 0.001$) compared to the $CVR < 1.6$ group (Table 1).

	CVR < 1.6 (n = 131)	CVR ≥ 1.6 (n = 14)	P-value
Maternal age (years)	29.98 ± 5.22	29.29 ± 4.86	0.636
Gestational age at diagnosis (weeks)	24.31 ± 2.69	23.79 ± 3.07	0.499
Fetal gender (male)	72 (55.0%)	5 (35.7%)	0.170
Lesion site (left)	71 (54.2%)	7 (50.0%)	0.765
Classification (Macrocystic (≥ 0.5 cm))	47 (35.9%)	12 (85.7%)	0.000
Concomitant malformations	13 (9.9%)	1 (7.1%)	1.000
mediastinal shift	53 (40.5%)	13 (92.9%)	0.000
Pleural/peritoneal effusion	1 (0.8%)	4 (28.6%)	0.000*
Maximum depth of amniotic fluid	4.47 ± 1.03	4.92 ± 1.27	0.130

Table 1. Prenatal characteristics. Significant values are in bold. *Fisher’s exact P -value. Categorical variables are presented as n (column percentages). Continuous variables (maternal age, gestational age, and amniotic fluid depth) are expressed as mean ± SD.

Comparison of surgical versus non-surgical groups

Groups In baseline comparisons, the surgical group exhibited higher risk factors, including a higher prevalence of prenatal CVR ≥ 1.6 (17.5% vs. 3.4%, $P=0.016$), increased postnatal respiratory symptoms (45.0% vs. 1.1%, $P<0.001$), and greater frequency of prenatal mediastinal shift (62.5% vs. 30.3%, $P=0.001$). No significant differences were observed regarding prenatal lesion location, maximum amniotic fluid depth, or prenatal pleural/abdominal effusion (Table 2).

Surgical likelihood over follow-up time

Kaplan–Meier survival analysis showed that the probability of surgery declined gradually over the initial 20 months post-birth, during which 95% of surgeries (38 cases) occurred, with an average surgical age of 7.53 ± 4.94 months. After 20 months, surgical rates decreased significantly, with only two additional cases (5%) at 24 and 41 months, respectively (Fig. 2).

Pediatric outcomes and sensitivity analysis

Factors influencing pediatric surgical decisions and timing were assessed using two models (Tables 3 and 4): Model 1 (prenatal variables only): Prenatal mediastinal shift significantly influenced surgical outcomes. Model 2 (including postnatal respiratory symptoms): Only postnatal respiratory symptoms were independently associated with surgical decisions and timing (all $P<0.001$ for original and multiple imputation by chained equations [MICE] data). Prenatal variables, including previously significant mediastinal shift, were no longer independently associated (all $P>0.05$).

A sensitivity analysis using multiple imputation by chained equations (MICE) assessed the robustness of findings. Results showed no significant differences in regression coefficients, standard errors, or P-values between models before and after imputation, confirming the reliability of conclusions despite missing data (Tables 3 and 4).

Discussion

Clinical value of CVR in prenatal CPAM monitoring

The CPAM CVR is a critical quantitative indicator for evaluating prenatal CPAM risk, reflecting lesion compression on intrathoracic structures. Extensive studies have consistently linked elevated CVR values with increased risks of fetal hydrops, prenatal interventions, and long-term surgical necessity^{11–13}. Our findings support these associations, showing significantly higher incidences of mediastinal shift and pleural/abdominal effusion in the CVR ≥ 1.6 group, along with a tendency towards increased amniotic fluid depth compared to the CVR < 1.6 group ($P = 0.13$). These results highlight the physiological cascade initiated by enlarging lesions: substantial mass effects cause mediastinal compression, impaired venous return, reduced fetal swallowing, and subsequent pleural/abdominal effusion and polyhydramnios¹⁴. Therefore, close monitoring of mediastinal shift, pleural/abdominal effusion, and amniotic fluid changes in fetuses with CVR ≥ 1.6 is essential to prepare for timely intervention¹⁵.

Additionally, the CVR ≥ 1.6 group demonstrated a significantly higher proportion of macrocystic lesions (≥ 0.5 cm) compared to the CVR < 1.6 group (85.7% vs. 35.9%, $P < 0.001$). This likely results from inherently larger volumes associated with macrocystic lesions, leading to elevated CVR. No significant differences were noted in maternal age, gestational age at diagnosis, fetal sex, associated anomalies, or lesion location, aligning with previous studies¹⁶.

Key factors influencing surgical decision-making

Univariate analysis identified prenatal CVR ≥ 1.6, mediastinal shift, and postnatal respiratory symptoms as significantly more common in the surgical group. Notably, 94.74% of symptomatic infants underwent surgery. Initially, these findings align with prior research highlighting the integration of prenatal indicators and postnatal clinical presentations in surgical decision-making^{3,14,17}. However, multivariate analysis incorporating postnatal symptoms showed that only respiratory symptoms independently influenced surgical decisions and timing ($P < 0.05$). This suggests prenatal factors such as high CVR and mediastinal shift primarily indicate a higher likelihood of developing postnatal symptoms rather than serving as direct surgical indications. Therefore, prenatal indicators like CVR primarily identify high-risk groups likely to require intervention, with clinical emphasis placed on postnatal respiratory symptoms when deciding surgery¹⁸. Additionally, lesion location (left or right lung) was not significantly associated with surgical decisions, differing from some reports suggesting

	Surgery(<i>n</i> = 40)	Non-operated(<i>n</i> = 89)	<i>P</i> -value
CVR(≥ 1.6)	7 (17.5%)	3 (3.4%)	0.016
Lesion site (left)	23 (57.5%)	45 (50.6%)	0.465
Respiratory symptoms	18 (45.0%)	1 (1.1%)	0.000
Pleural/peritoneal effusion	3 (7.5%)	1 (1.1%)	0.167
mediastinal shift	25 (62.5%)	27 (30.3%)	0.001
Maximum depth of amniotic fluid	4.70 ± 1.13	4.48 ± 1.00	0.265

Table 2. Comparison of characteristics between surgical and non-surgical groups. Significant values are in bold. The percentage is the column percentage.

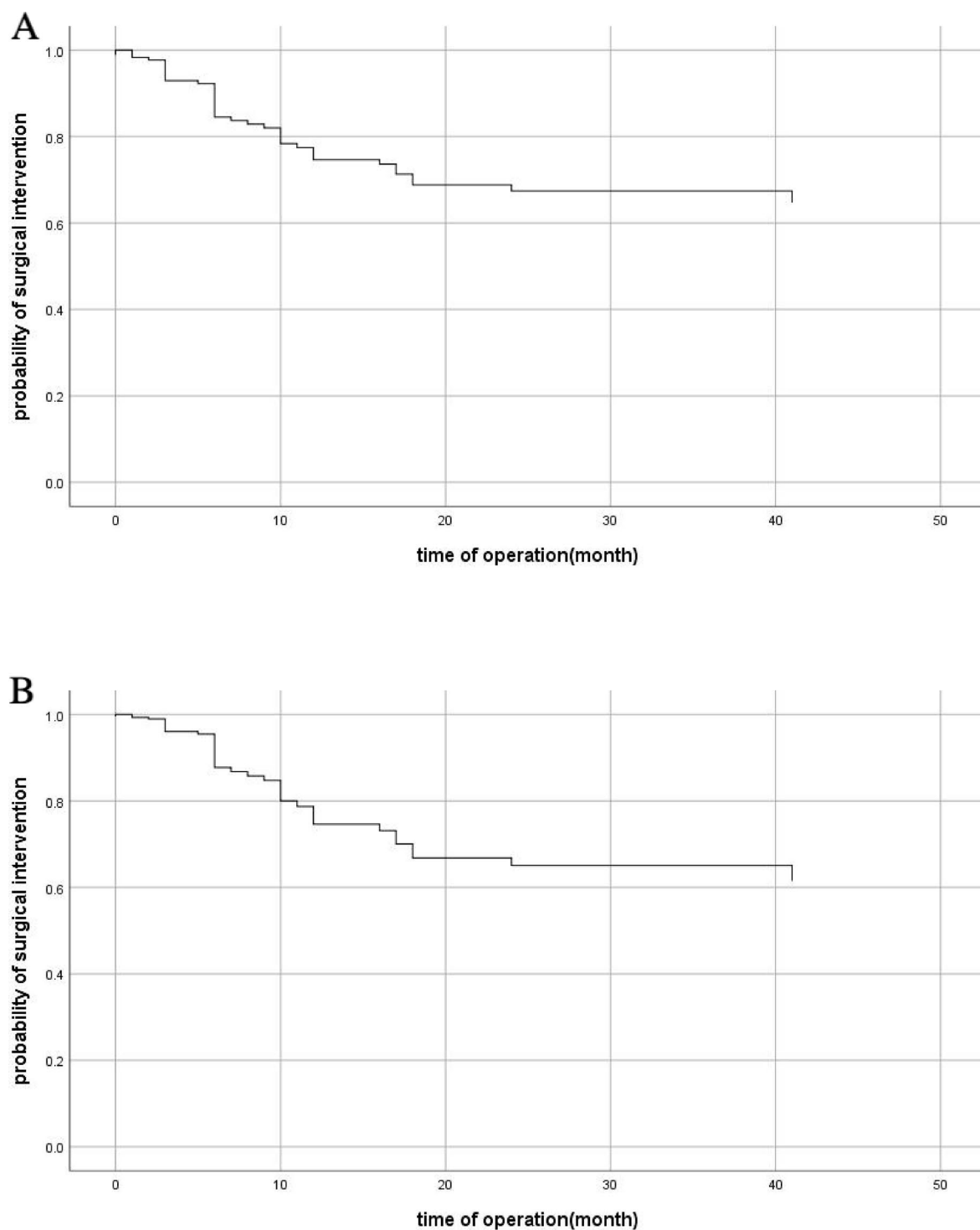


Fig. 2. Relationship between surgery likelihood and follow-up duration (raw data). Survival curve analysis indicates a declining probability of surgical intervention within the first 20 months post-birth. Beyond 20 months, the surgery rate stabilizes at a minimal level. (A) Model 1: Prenatal variables only and (B) Model 2: Prenatal variables + Postpartum respiratory symptoms both demonstrate 'the trend of surgical intervention probability with age.

Model	Characteristics	Neonatal prognosis (raw data)			Neonatal prognosis (MICE data)		
		Coefficient	Standard error	P-value	Coefficient	Standard error	P-value
Model 1	Mother's age	0.022	0.047	0.642	0.022	0.046	0.634
	Gestational age (GA)	−0.130	0.097	0.180	−0.154	0.091	0.093
	Fetal gender (male)	0.323	0.426	0.449	0.195	0.408	0.633
	lung disease lesion location (left side)	0.084	0.443	0.849	0.208	0.422	0.622
	CPAM classification (macrocytic type (≥ 0.5 cm))	0.879	0.454	0.053	0.829	0.437	0.058
	CVR(≥ 1.6)	0.541	0.911	0.552	0.546	0.894	0.541
	mediastinal shift	1.044	0.460	0.023	1.213	0.438	0.006
	Concomitant malformations	−0.551	0.913	0.546	0.033	0.784	0.966
	Combined pleural/peritoneal effusion	0.271	1.378	0.844	0.322	1.372	0.815
	Maximum depth of amniotic fluid	0.262	0.210	0.212	0.238	0.209	0.254
	Mother's age	0.011	0.053	0.831	0.015	0.053	0.777
	Gestational age (GA)	−0.096	0.104	0.356	−0.112	0.100	0.263
Model 2	Fetal gender (male)	0.279	0.485	0.566	0.167	0.473	0.723
	lung disease lesion location (left side)	0.003	0.496	0.995	0.072	0.482	0.881
	CPAM classification (macrocytic type (≥ 0.5 cm))	0.562	0.521	0.280	0.523	0.508	0.303
	CVR(≥ 1.6)	0.055	1.178	0.963	0.177	1.189	0.882
	mediastinal shift	0.527	0.536	0.325	0.591	0.521	0.257
	Concomitant malformations	−0.527	1.070	0.622	−0.301	1.020	0.768
	Combined pleural/peritoneal effusion	−0.821	2.001	0.681	−0.898	2.093	0.668
	Maximum depth of amniotic fluid	0.139	0.239	0.562	0.114	0.243	0.640
	Respiratory symptoms	3.874	1.132	0.001	4.103	1.123	0.000

Table 3. Logistic regression and sensitivity analysis of pediatric patient prognosis (surgery performed or not). Significant values are in bold. Legend: Logistic regression assessed factors influencing the decision to perform surgery postnatally. Model 1 included prenatal variables only; Model 2 included prenatal variables plus postnatal respiratory symptoms. Results from raw and multiple imputation by chained equations (MICE) data are shown. SE = standard error.

lobe-specific symptom impacts and management strategies¹⁹. This inconsistency might stem from ultrasound limitations in precisely identifying specific lung lobes.

CPAM management: balancing observation and intervention

Maternal steroid therapy was not administered to 14 cases with CPAM CVR ≥ 1.6 (12 macrocystic and 2 microcystic lesions) for several reasons. First, existing literature³ states that steroids are ineffective for macrocystic lesions. Second, fetal hydrops significantly worsens prognosis; however, among these 14 cases, only 4 presented with pleural/abdominal effusions, insufficient for hydrops diagnosis and thus not meeting the criteria for steroid use in high-risk cases²⁰. Additionally, steroids may increase maternal gestational diabetes risk²¹. After careful consideration, prenatal ultrasound monitoring was prioritized.

Two cases receiving maternal steroids were excluded to maintain the accuracy of the prenatal-postnatal outcomes analysis. Steroids can temporarily reduce lesion size, interfering with accurate CVR assessments and causality inferences regarding lesion compression.

Findings confirmed postnatal respiratory symptoms as the primary indication for surgical intervention, consistent with previous research^{22,23}. Among asymptomatic patients, 22 (20%) underwent surgery due to large lesion volumes and parental concerns about potential infection or disease progression. This aligns with recommendations from experts advocating proactive surgical intervention to mitigate long-term risks²⁴. However, extended follow-up supports conservative management. Over a mean follow-up of 27.18 ± 19.06 months (range: 1–72 months), no malignant transformations were detected among the 129 surviving CPAM cases. Pathological examinations of surgical cases showed no malignancies, and conservatively managed patients had regular clinical follow-ups every 3–6 months in the first year and every 6–12 months thereafter (primarily using lung ultrasound, supplemented by X-ray or low-dose CT). No malignancy-related symptoms such as unexplained fever, growth delays, or persistent cough were observed. Imaging studies showed no rapid lesion enlargement or malignant features, indicating low malignancy risk. These results support the safety of active surveillance for asymptomatic, stable infants^{3,25,26}.

Optimal surgical timing should be individualized. Survival analysis demonstrated that 95% of surgeries occurred within the first 20 months, with a mean surgical age of 7.53 ± 4.94 months, after which surgical rates sharply declined. This suggests that asymptomatic infants who remain stable in early childhood, especially within the first 20 months, have a lower long-term likelihood of requiring surgery. Consequently, an active surveillance approach until around 20 months of age could effectively minimize premature interventions and unnecessary lung tissue removal, reducing potential long-term effects on pulmonary function^{5,6,27}.

Model	Characteristics	Neonatal prognosis (raw data)			Neonatal prognosis (MICE data)		
		Coefficient	Standard error	P-value	coefficient	Standard error	P-value
Model 1	Mother's age	0.008	0.035	0.831	0.008	0.035	0.824
	Gestational age (GA)	− 0.126	0.081	0.121	− 0.141	0.078	0.070
	Fetal gender (male)	0.118	0.344	0.732	0.061	0.330	0.855
	lung disease lesion location (left side)	− 0.011	0.344	0.974	0.076	0.330	0.818
	CPAM classification (macroscopic type (≥ 0.5 cm))	0.591	0.363	0.104	0.566	0.351	0.107
	CVR(≥ 1.6)	0.138	0.572	0.810	0.220	0.572	0.700
	mediastinal shift	0.811	0.361	0.025	0.902	0.350	0.010
	Concomitant malformations	− 0.087	0.751	0.908	0.305	0.619	0.623
	Combined pleural/peritoneal effusion	1.002	0.765	0.190	1.032	0.765	0.177
	Maximum depth of amniotic fluid	0.260	0.179	0.146	0.237	0.182	0.191
Model 2	Mother's age	− 0.045	0.040	0.260	− 0.029	0.037	0.435
	Gestational age (GA)	− 0.117	0.087	0.178	− 0.109	0.082	0.183
	Fetal gender (male)	0.119	0.357	0.739	0.032	0.339	0.924
	lung disease lesion location (left side)	− 0.081	0.351	0.817	− 0.025	0.342	0.941
	CPAM classification (macroscopic type (≥ 0.5 cm))	0.646	0.373	0.083	0.603	0.368	0.101
	CVR(≥ 1.6)	0.205	0.547	0.707	0.421	0.539	0.435
	mediastinal shift	0.101	0.407	0.804	0.094	0.404	0.816
	Concomitant malformations	0.151	0.767	0.844	0.137	0.625	0.827
	Combined pleural/peritoneal effusion	0.905	0.771	0.241	0.910	0.764	0.233
	Maximum depth of amniotic fluid	0.225	0.206	0.273	0.235	0.204	0.250
	Respiratory symptoms	2.667	0.420	0.000	2.695	0.410	0.000

Table 4. Cox regression and sensitivity analysis for neonatal prognosis (surgery timing). Significant values are in bold. Legend: Cox regression analyzed factors influencing the timing of surgical interventions. Model 1 contained prenatal variables only; Model 2 added postnatal respiratory symptoms. Both raw and MICE-imputed data results are presented. SE = standard error. Raw data Model 1: Omnibus test $\chi^2 = 21.624$, $P = 0.017$; Model 2: $\chi^2 = 59.919$, $P < 0.001$. MICE data Model 1: Omnibus test $\chi^2 = 25.059$, $P = 0.005$; Model 2: $\chi^2 = 67.702$, $P < 0.001$.

Limitations and future directions

Several limitations should be acknowledged. First, the retrospective design relies on existing medical records, resulting in incomplete prenatal dynamic data, preventing detailed analysis of CPAM CVR trends. Second, while the overall sample size is adequate, the subgroup with CVR ≥ 1.6 ($n = 14$) is relatively small, potentially reducing statistical power. Third, the analysis did not deeply explore other potential predictive factors for surgical decision-making, such as oxygen therapy and mechanical ventilation requirements. Fourth, prenatal ultrasound limitations in identifying specific lung lobes might underestimate the impact of lesion location on prognosis. Finally, the current follow-up duration is insufficient for fully evaluating long-term pulmonary function and malignancy risk.

Future studies should expand the sample size using multicenter prospective cohorts, collect serial prenatal CVR data for trend analysis, and incorporate advanced techniques such as genetic testing, artificial intelligence-based imaging, and fetal magnetic resonance imaging (MRI). These methods could contribute to developing personalized risk assessment models that combine prenatal and postnatal data, enhancing clinical decision-making.

Conclusion

Postnatal respiratory symptoms primarily determine the clinical decision for surgical intervention in infants with CPAM. While prenatal ultrasound parameters (CVR, mediastinal shift) provide crucial information for fetal risk assessment and monitoring, they should not independently dictate surgical decisions postnatally. Instead, they serve as indirect indicators of surgical risk through their association with symptom development. Conservative management is safe and feasible for asymptomatic infants; however, respiratory symptoms strongly indicate the need for surgical intervention.

Data availability

The datasets and analysis codes used and/or analyzed in this study are available for peer review and reuse. These materials can be obtained from the corresponding author upon reasonable request. Requesters must provide a statement specifying the research purpose and an ethical review certificate. Materials are provided solely for academic research purposes.

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Author contributions

Yutian Miao : Participated in the study design, data collection and analysis, and was responsible for drafting the initial manuscript. Sheng Wang: Responsible for data collection and image collection. Jiyuan Li : Responsible for data collection and information analysis. Sisi Peng : Responsible for data collation and literature collation. Hui Cao: Responsible for literature collation and data collation. Yingchun Luo : Participated in the discussion of the research plan and revised and reviewed the manuscript. Haiyan Kuang : As the corresponding author, responsible for the overall research design of the project, funding acquisition, and the final review and guidance of the manuscript. All authors reviewed the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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