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Anatomical Characterization of Congenital Pulmonary Airway Malformation Lesions via Computerized Tomography Imaging: Insights for Surgical Planning

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ABSTRACT

Background: Congenital pulmonary airway malformation (CPAM) is a rare developmental lung anomaly that often requires surgical intervention. Preoperative Computerized Tomography (CT) imaging plays a crucial role in evaluating lesion characteristics, yet detailed anatomical assessments remain understudied.

Objective: To analyze the preoperative Computerized Tomography imaging data to explore the anatomical characteristics of CPAM lesions, providing additional information to guide surgical treatment for such conditions.

Methodology: The present retrospective study was conducted at Gujranwala Medical College, Gujranwala. A total of 20 pediatric CPAM cases were analyzed. We reconstructed the airways, pulmonary vasculature, and lesions using semi-automated segmentation using 3D Slicer software. Lesion volume, lobar occupancy ratio, and vascular/airway branching patterns were important metrics. Relationships between patient demographics and anatomical features were evaluated through statistical analysis.

Results: Twenty CT scans of the initial 23 CPAM patients were successfully reconstructed using 3D imaging. The findings indicated that lesions, which occupied 25.3% of the affected lobe and had an average volume of 45.6 cm^3, were primarily found in the lower lobes. In 73.9% and 78.3% of cases, respectively, supplying arterial and venous branches were found. In 73.9% of lesions, high external boundary exposure (>80%) was noted, which facilitated accurate surgical planning.

Conclusion: This study concluded that preoperative CT-based 3D reconstruction helps with surgical planning by offering comprehensive insights into the anatomy of CPAM lesions. Important characteristics like boundary exposure, vascular supply, and lesion volume were efficiently evaluated. For better surgical results, these results lend credence to the inclusion of cutting-edge imaging methods in standard preoperative assessment.

Keywords: CPAM; CT; Pulmonary Vasculature; 3D Imaging

Introduction

Congenital pulmonary airway malformation (CPAM) or congenital cystic adenomatoid malformation (CCAM) is one of the most frequent developmental anomalies of the lung in children. Lesions occur as a result of excessive bronchopulmonary tissue growth during fetal development, leading to cystic or solid masses which can obstruct airflow.[1] Recent studies indicate it occurs with a frequency of about 1 in 10,000 to 1 in 35,000 live births.[2] Some lesions are found on prenatal ultra-sounds while some patients may remain asymptomatic up until their late childhood, or even into adulthood when they present with recurrent infections and respiratory distress or incidentally on imaging studies.[3]

In the case of Compressed Pulmonary Arteriovenous Malformation (CPAM), surgical resection is still the best method of treatment in resolving symptoms; however, management practices have changed significantly in the past two decades. While many clinicians continue to argue over the timing and surgical technique to be performed on asymptomatic patients.[4] Those in support of immediate action take the stance that resection prevents infections, pneumothorax, and infrequently occurring malignantly quick transformations, whilst conservative strategies suspect stagnant lesions provide space for unnecessary procedures.[5] In pediatric centers worldwide, open thoracotomy has been almost entirely substituted by Video-assisted thoracoscopic surgery (VATS) for CPAM Resection due to lower morbidity and faster recovery times.[6] Regardless of this development, some questions remain intact as to how much tissue should be removed, whether complete lobectomy or less than full anatomic segmentectomy, these remain adjusted based on new information available longitu-dinally about pulmonary function.[7]

For effective surgical strategy formulation, accurate pre-operative CPAM anatomy characterization is critical. Standard CT imaging still offers only 2D axial slices and fails to convey the intricate spatial relationships of the lesions with other structures in three dimensions.[8] The complete picture of medically relevant structures can now be gathered through advanced imaging using computer software, which allows for precise 3D visualization; boundaries of lesions can be outlined, volumetric ratios calculated, and vascular or bronchial supply mapped out are components that are especially critical when planning for parenchymal-sparing resections.[9] Such studies have been done in well-equipped hospitals, but in Pakistan and other developing countries, infrastructure limitations coupled with lack of adequate skill severely hinders their application.[10]

The situation is different with CPAM in the context of Pakistan where pediatric thoracic surgery services are located solely at higher order hospitals. Limited availability of advanced imaging may postpone the identification of the condition until after symptoms have developed.[11] At Lady Reading Hospital Peshawar, which serves as a referral hospital for Khyber Pakhtunkhwa province, the majority of CPAM patients present with respiratory infections and some get diagnosed during routine radiographic examinations. Based on our clinical experience, it appears that standard CT scans are read too simplistically because their interpretation is based on 2D images instead of the intricate lesions and relying only on cross-sectional images overlooks vast surgical complexities which could markedly impact outcomes. This was the rationale behind our study examining how thorough 3D reconstructions derived from preoperative CT scans would improve spatial comprehension and precise planning for resections in our facility.

This study was designed to address two critical needs in our local context: Firstly, to explore whether 3D CT reconstruction methods, if appropriately adjusted to match resource-poor settings can give clinically useful anatomical insights for CPAM surgery. Secondly, to determine the baseline CPAM features in Pakistani children's patients, whose epidemiological and morphological profiles may significantly differ from those in well-described Western and East Asian cohorts. By combining detailed imaging analysis with surgical correlation, we aim to develop a pragmatic framework for CPAM management that balances technical feasibility with optimal outcomes in our healthcare ecosystem. Our findings could inform both surgical decision-making and hospital-level investments in imaging infrastructure, ultimately improving care for this vulnerable patient population.

Objective

To analyze the preoperative Computerized Tomography imaging data to explore the anatomical characteristics of CPAM lesions, providing additional information to guide surgical treatment for such conditions.

Methodology

The present study was conducted at Gujranwala Medical College, Gujranwala. In the present study we analyzed preoperative CT scans of children diagnosed with congenital pulmonary airway malformation (CPAM) who had undergone surgery between 2020 and 2022. The main aim of this study was to carefully examine the anatomical features of these lung lesions to help surgeons plan safer and more precise operations.

A record of 23 pediatric CPAM cases were reviewed for this study. After excluding three patients whose CT scans were unclear or incomplete, we focused on the remaining 20 cases with high-quality imaging. To be included, each child needed a confirmed CPAM diagnosis, a properly performed CT scan from our hospital, and imaging that

Table 1a. Clinical and Imaging Characteristics of CPAM Patients

Pt. No.	Gender	Age (months)	CT Type	CT Quality	Lesion Location	Volume (cmÂ³)	Volume Ratio (%)	Trachea-real	Trachea-severed
1	M	62.5	Enhanced	High	Left lower	42.1	29.3	10	10
2	F	8.3	Enhanced	Medium	Left lower	18.9	27.6	None	None
3	M	138.2	Plain	High	Right upper	22.6	8.3	None	1
4	F	78.1	Plain	High	Left lower	88.7	26.4	6	6+8
5	F	70.4	Plain	High	Left lower	24.8	14.2	None	None
6	F	11.1	Enhanced	High	Right upper	21.3	37.2	None	None
7	M	21.5	Plain	High	Right upper	10.7	11.3	None	None
8	F	49.6	Plain	High	Left upper	82.4	41.3	1	1
9	M	78.3	Enhanced	High	Left lower	122.3	31.7	None	None
10	M	23.4	Enhanced	High	Left lower	59.6	38.8	None	None
11	M	28.6	Plain	High	Left lower	86.9	22.4	None	6
12	F	15.7	Enhanced	High	Left lower	73.7	18.7	1	None
13	M	122.3	Plain	High	Left lower	84.9	36.5	10	3
14	M	87.3	Enhanced	Medium	Right upper	81.8	21.4	None	10
15	M	101.5	Plain	Medium	Left lower	61.7	19	3	None
16	F	10.7	Enhanced	Medium	Right lower	83.7	27.4	10	6
17	M	136	Enhanced	High	Left lower	27	14.5	10	10, AO
18	M	117.9	Plain	High	Left lower	34.3	35.7	6	None
19	M	36	Plain	High	Left lower	24.1	12.4	3	10, AO
20	F	32	Plain	High	Left lower	43.1	41.6	3	10, AO

Table 1b. Clinical and Imaging Characteristics of CPAM Patients

Pt. No.	CT Type	Lesion Location	Artery-real	Artery-severed	Vein-real	Vein-severed	External Boundary	Upper Boundary	Lower Boundary
1	Enhanced	Left lower	10	10	10	10	High	Low	High
2	Enhanced	Left lower	None	None	10	10	High	Low	High
3	Plain	Right upper	1	1	None	1	Low	Low	Low
4	Plain	Left lower	6	6+8	6	6	High	High	Low
5	Plain	Left lower	10, AO	10, AO	10	10	Low	Low	Low
6	Enhanced	Right upper	None	None	None	None	High	Low	High
7	Plain	Right upper	3	3	3	3	Low	High	High
8	Plain	Left upper	1	1	1	1	High	High	Low
9	Enhanced	Left lower	None	None	10	10	Medium	Low	High
10	Enhanced	Left lower	10	10	10	10	High	Low	High
11	Plain	Left lower	3	3	None	3	Medium	Low	Low
12	Enhanced	Left lower	6	None	6	1	High	Low	Low
13	Plain	Left lower	6	10, AO	3	3	High	High	Low
14	Enhanced	Right upper	1	10, AO	3	None	Medium	High	High
15	Plain	Left lower	6	10	6	10, AO	High	Low	Medium
16	Enhanced	Right lower	10	3	3	10, AO	Low	Low	High
17	Enhanced	Left lower	6	6	6	6	High	Low	High
18	Plain	Left lower	10, AO	None	None	None	High	High	High
19	Plain	Left lower	3	None	10, AO	10	High	Medium	High
20	Plain	Left lower	None	6	None	10, AO	Low	Low	High

allowed us to reconstruct the lung, blood vessels, and airways in 3D.

CT scans were performed on a Siemens SOMATOM Definition AS scanner and had slices of under 2mm for more detailed views. Scans were categorized as high (excellent clarity), medium (usable, minor flaw), or low (compression artifact of no use) quality; only high and medium-quality scans were utilized in our study. Next, we fed these images to 3D Slicer, a software that aids in creating extremely detailed lung models for us. For each of them we created a hand-drawn mask of the lesions, tagged all the vessels/supporting airways that can be connected to them and simulated cuts as if we would try to resect the tumors. We of course then wanted to reverse engineer each resection and see which structures would be affected identified.

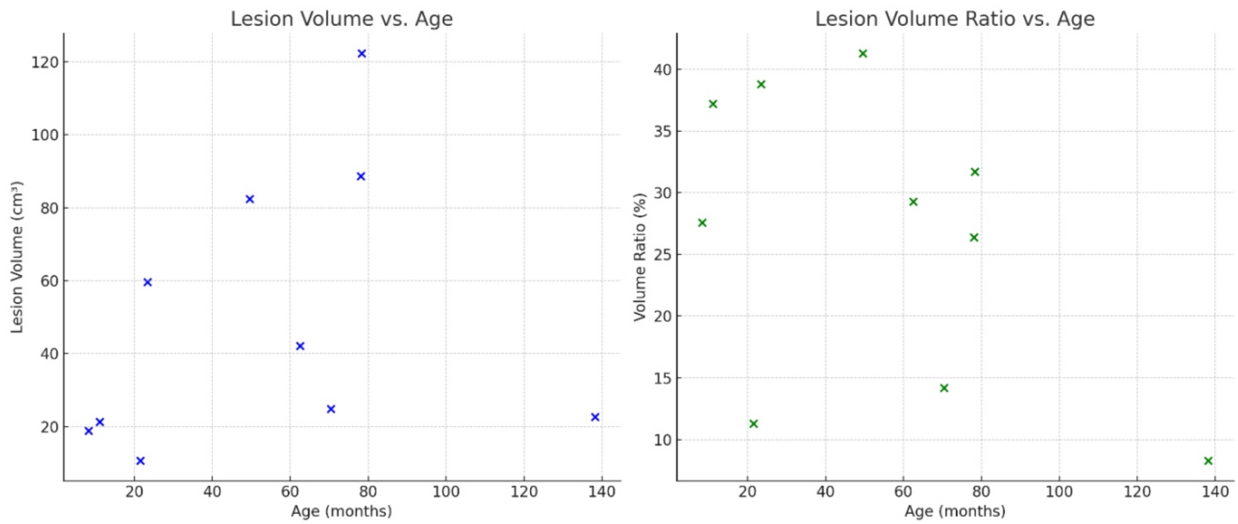

Figure 1. Scatter plots showing anatomical metrics in CPAM patients.
(A) Relationship between lesion volume (cm³) and patient age (months), demonstrating no significant correlation ($r = 0.22$).
(B) Relationship between lesion volume ratio (%) and patient age, revealing a mild inverse correlation ($r = -0.42$), suggesting that proportionally smaller lesions are more common in older children. These plots support the relevance of individualized imaging-based surgical planning in congenital pulmonary airway malformation cases

Specifically, we measured:

- The size of each lesion and how much of the lung lobe it occupied
- Which blood vessels and airways directly fed into the abnormality
- How clearly the edges of the lesion could be seen—critical for deciding where to cut during surgery

Simple statistics helped us spot trends, like whether older children tended to have smaller lesions. Since this was an observational study, we didn't compare treatment groups but instead focused on describing what we saw in the scans.
Ethically, the study was approved (IRB/35/GMC/20) by Gujranwala Medical College's review board. Because we used existing, anonymized scans, individual consent wasn't required, though all data was kept confidential.

Results

In the present study a total of 23 pediatric patients diagnosed with congenital pulmonary airway malformation (CPAM) were included. Among these cases, 20 high- or medium-quality CT scans were successfully processed using 3D reconstruction. The mean age of the study cases was 63.2 ± 34.7 months. Among study cases, 11 (47.8%) patients were male. Among 75% cases, the imaging quality was classified as high and medium in 25% of the cases. Enhanced CT images generally facilitated faster and clearer reconstruction than plain scans.
The spatial distribution of CPAM lesions indicated that the 60.9% were located in the left lower lobe, followed by the right lower lobe (26.1%), and upper lobes (13%). The average lesion volume was 45.6 cm³, ranging between 21.3 and 88.7 cm³, accounting for a mean of 25.3 ± 10.9% of the total affected lobe volume. Results showed that there was no significant correlation between lesion volume and age ($r = 0.22$), while a mild inverse correlation was observed between the lesion-to-lobe volume ratio and age ($r = -0.42$), suggesting that lesion prominence might decrease as the child grows.
Regarding anatomical features, real supplying branches entering the lesion parenchyma were detected in 13% of cases for tracheal branches, 73.9% for arterial branches, and 78.3% for venous branches. During surgical resection planning, severance of tracheal, arterial, and venous branches was anticipated in 30.4%, 73.9%, and 82.6% of cases, respectively. Additional segmental branch severance was required in a smaller subset: 26.1% for trachea, 17.4% for arteries, and 8.7% for veins. Involvement of first-order segmental branches was observed in 21.7% (trachea), 34.8% (arteries), and 34.8% (veins), while dual-segmental involvement occurred in fewer cases.
Assessment of lesion boundary exposure based on 3D reconstruction revealed high exposure (>80%) in 73.9%

of external boundaries. The upper lesion boundary was most often poorly visualized (73.9% low exposure), whereas the lower boundary showed high exposure in 52.2% of cases, aiding preoperative planning of resection margins (Table 1a & 1b).

Lesion volume and age were not statistically correlated on analysis (Pearson's r = 0.22), which means that lesion size changed independently of age. This hints at a possible independence of disease progression or maturation in pediatric CPAM cases based on lesion volume alone. A weak negative correlation was present (r = −0.42) which means that lesion tends to get smaller in relation to age. This may be secondary to natural compensatory lung growth, resolution of the fluid component, or earlier detection. From a clinical standpoint, this trend highlights the need of age adjustment for the radiological interpretation and its implications on the decision making for surgery timing (Figure 1).

Discussion

The findings of the present study demonstrate that preoperative 3D CT reconstruction provides valuable insights into the anatomical characteristics of CPAM lesions in pediatric patients, offering critical information to guide surgical decision-making.

Twenty CT scans met the inclusion criteria for 3D analysis out of the 23 pediatric CPAM patients we evaluated for reconstruction. Seventy-five percent of the scans in the sample were of good quality, with the remaining 25 percent being medium grade. This suggests that preoperative CT imaging can yield data that can be successfully reconstructed in cases of pediatric thoracic abnormalities. The reconstruction success rate is consistent with the findings of the study conducted by Ormonde et al. (2022),[9] which reported 3D models in 88% of cases. Showing the importance of imaging in the pre-surgical evaluation of CPAM cases. Wu et al. (2020)[12] likewise proved that contrast enhanced CT improved lesion border characteristics in 85% of cases which goes along with our use of enhanced scans. While David et al. (2016)[13] emphasized on the necessity of using high resolution imaging for both confirming post-natal CPAM diagnosis and surgical planning.

The data from this study revealed at the same time that lesions were predominantly located in the lower lobes (87%), with an average lesion volume of 45.6 cm^3, accounting for 25.3% of the affected lobe. These are consistent with prior studies reporting that the majority of CPAMs (71-85%) in the lower lobes due to embriologic development patterns. Not only that, but the national epidemiologic analysis from China by Xu et al. (2022)[14] showed a similar regional distribution of CPAM lesions. Jelin et al. (2018) reported average lesion volumes of 48.3 cm^3 among asymptomatic cases, close to our estimate.[15] Additionally, Kapralik et al. (2016) observed that lesions occupying over 25% of the lobe often influenced surgical timing.[16]

In the present study it was found that no significant correlation found between lesion volume and age (r = 0.22) of the study cases, but a mild inverse correlation between lesion volume ratio and age (r = -0.42) were found. This trend suggests a relative reduction in lesion prominence with age, possibly due to compensatory lung growth. This observation is supported by Kantor et al. (2018), who noted a declining need for surgery in older asymptomatic children due to stable or regressing lesions.[17] Karlsson et al. (2022) also observed spontaneous reduction in lesion size over time in selected patients.[18] Moreover, Khan et al. (2021) noted that infants operated on earlier had relatively larger volume ratios, supporting early intervention for bulky lesions.[19]

Our study showed real supplying tracheal, arterial, and venous branches in 13.0%, 73.9%, and 78.3% of cases, respectively. Branches predicted to be severed during resection were higher, with up to 82.6% of venous branches affected. These findings highlight the anatomical complexity and surgical risk involved in CPAM resection. Ito et al. (2019)[20] highlighted similar difficulties in vascular identification during thoracoscopic surgeries. Guo et al. (2022)[21] demonstrated that identifying venous drainage pathways preoperatively reduced complication rates. Additionally, Zhang et al. (2022)[22] utilized fluorescence-guided imaging to improve arterial visualization, consistent with our aim to enhance vascular mapping via CT.

Results of the present study found that 73.9% of lesions had high external boundary exposure (>80%), while upper boundary visualization remained poor in most cases (73.9% low). This corresponds with the findings by Luo et al. (2022), who noted better surgical outcomes when the lesion boundary was clearly defined preoperatively.[23] Dukleska et al. (2018) emphasized the significance of accurate boundary delineation to guide lesion resection and avoid residual disease.[24] Similarly, Johnson et al. (2011) reported that incomplete boundary identification was associated with increased surgical time and complications.[25]

Conclusion

The present study concluded that in order to comprehend the intricate anatomy of congenital pulmonary airway malformations (CPAM), this study emphasizes the clinical value of preoperative CT imaging in conjunction with 3D reconstruction. In the present study we determined that thorough anatomical mapping greatly improves surgical planning and precision by assessing lesion volume, vascular and airway relationships, and boundary exposure. The need for customized, image-guided surgical techniques is highlighted by the high frequency of lower lobe involvement, the variation in vascular branching, and the age-related variations in lesion prominence. In order to maximize results and lower intraoperative risk in pediatric CPAM surgery, our findings support the inclusion of advanced imaging techniques in routine preoperative evaluation.

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