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Morphological and Morphometric Variations of the Caudate Lobe of Liver and Its Clinical Significance: A Cross-Sectional Anatomical Study

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ABSTRACT

Background: The caudate lobe of the liver exhibits significant anatomical variability in its morphology and morphometry. These variations hold substantial importance in radiological interpretation, hepatic surgeries, and liver transplantation. Understanding these variations is essential to avoid diagnostic errors and surgical complications.
Aim: To study the morphological variations and morphometric parameters of the caudate lobe of the liver and evaluate their clinical significance.
Materials and Methods: This cross-sectional observational study was conducted on 100 liver specimens. Parameters studied included transverse diameter (TD), vertical diameter (VD), anteroposterior diameter (APD), number of notches, presence of fissure, shape of caudate lobe, morphology of papillary process, and porta hepatis measurements. Data were recorded and analyzed using descriptive statistics.
Results: The most common shapes of the caudate lobe were elongated (29%) and pyriform (29%). Two notches were present in 86% of cases. Fissure was observed in 71% of specimens. Papillary process was most commonly rounded (29%) or absent (29%). The mean TD, VD, and APD were 23.2 ± 7.8 mm, 51.7 ± 8.5 mm, and 24.4 ± 9.8 mm respectively. Porta hepatis showed greater transverse than vertical dimensions. Significant variability was observed in all parameters.
Conclusion: The caudate lobe shows considerable anatomical variability in both shape and dimensions. Awareness of these variations is crucial for radiologists and surgeons to ensure accurate diagnosis and safe surgical interventions.

Keywords*: Caudate lobe, liver anatomy, morphometry, papillary process, porta hepatis, anatomical variations.*

INTRODUCTION

The liver is the largest gland in the human body and plays a vital role in metabolism, detoxification, and digestion. Anatomically, it is divided into right and left lobes, with the caudate lobe representing a distinct and functionally significant segment located on the posterior surface of the liver [1]. The caudate lobe is unique due to its independent vascular supply and venous drainage directly into the inferior vena cava, distinguishing it from other hepatic segments [2].

The morphology of the caudate lobe has been a subject of considerable interest due to its clinical relevance in hepatic surgeries and radiological assessments. Variations in its shape, size, and surface features such as notches and fissures may influence surgical approaches, especially during hepatic resections and liver transplantation [3,4]. The caudate lobe is also known to undergo hypertrophy in certain pathological conditions such as liver cirrhosis, making its morphometric evaluation particularly important in diagnostic imaging [5].

Previous anatomical studies have demonstrated that the caudate lobe exhibits significant variability in shape, including elongated, pyriform, rectangular, triangular, and tongue-shaped forms [6,7]. These variations may arise due to differences in embryological development, particularly in the rotation and segmentation of hepatic tissue during fetal life [8]. Such

diversity in morphology necessitates a comprehensive understanding to avoid misinterpretation during imaging studies such as CT and MRI [9].

The presence and number of notches on the caudate lobe also vary among individuals. These notches may correspond to impressions from adjacent structures or vascular indentations and can serve as important anatomical landmarks [10]. Similarly, the presence or absence of fissures within the caudate lobe may influence its segmentation and surgical accessibility [11].

Another important structure associated with the caudate lobe is the papillary process, which may present in different shapes such as rounded, pointed, conical, or may be completely absent [12]. A prominent papillary process may sometimes mimic pathological masses on imaging, leading to diagnostic confusion [13]. Therefore, knowledge of its normal variations is essential for clinicians and radiologists.

Morphometric parameters such as transverse diameter (TD), vertical diameter (VD), and anteroposterior diameter (APD) provide quantitative assessment of the caudate lobe. These measurements are particularly useful in evaluating hepatic enlargement, atrophy, or segmental hypertrophy in various liver diseases [14,15]. Studies have shown that the caudate lobe tends to enlarge disproportionately in cirrhosis, making it a useful parameter in radiological diagnosis [16].

The porta hepatis, which transmits the portal triad structures, is closely related to the caudate lobe. Variations in its dimensions may affect surgical procedures such as liver transplantation and hepatic resections [17]. Accurate knowledge of porta hepatis anatomy is therefore crucial for minimizing intraoperative complications.

Despite several studies on liver morphology, there remains a need for comprehensive evaluation of the caudate lobe, particularly in the Indian population, where anatomical variations may differ due to genetic and environmental factors [18,19]. Most previous studies have focused either on morphology or morphometry, but few have integrated both aspects in a single study [20].

The present study aims to provide a detailed analysis of both morphological and morphometric variations of the caudate lobe, including its shape, notches, fissures, papillary process, and associated measurements. Such data will contribute to the existing anatomical knowledge and provide valuable insights for clinicians involved in hepatobiliary surgery and diagnostic imaging [21–23].

Understanding these variations is particularly important in modern surgical practice, where minimally invasive and segmental liver surgeries are increasingly performed [24]. Precise anatomical knowledge reduces the risk of complications such as hemorrhage and bile duct injury [25].

Furthermore, with the advancement of imaging techniques, subtle anatomical variations are more frequently detected, emphasizing the need for correlating radiological findings with anatomical data [26,27]. This study therefore serves as a bridge between anatomical research and clinical application.

In conclusion, the caudate lobe is a highly variable structure with significant clinical importance. A thorough understanding of its morphology and morphometry is essential for accurate diagnosis, effective surgical planning, and improved patient outcomes [28–35].

MATERIALS AND METHODS

This cross-sectional descriptive anatomical study was conducted on **100 adult human liver specimens** obtained from the Department of Anatomy of a tertiary care medical institution. The study was carried out over a period of one year after obtaining approval from the Institutional Ethics Committee.

Inclusion Criteria

- Adult human liver specimens
- Specimens with intact caudate lobe
- Livers without gross pathological abnormalities

Exclusion Criteria

- Damaged or mutilated liver specimens
- Specimens with visible tumors, cirrhosis, or trauma
- Pediatric liver specimens

Study Parameters

Each liver specimen was carefully examined for the following parameters:

1. **Morphological Parameters**
    - Shape of caudate lobe (elongated, pyriform, rectangular, triangular, tongue-shaped, oval)
    - Number of notches present
    - Presence or absence of fissure
    - Shape of papillary process (rounded, pointed, conical, triangular, absent)
2. **Morphometric Parameters**
    - Transverse diameter (TD) of caudate lobe (mm)
    - Vertical diameter (VD) of caudate lobe (mm)
    - Anteroposterior diameter (APD) (mm)
    - Porta hepatis dimensions (VD and TD)
    - Transverse diameter of right lobe

Method of Measurement

All measurements were taken using a **digital Vernier caliper** with an accuracy of 0.01 mm. Each parameter was measured twice and the average value was recorded to minimize observational error.

- **TD**: Maximum horizontal width of caudate lobe
- **VD**: Maximum vertical height
- **APD**: Maximum anteroposterior thickness
- **Porta hepatis measurements** were taken at the widest visible opening

Data Analysis

Data were compiled in Microsoft Excel and analyzed using descriptive statistics.

- Mean, standard deviation (SD), and range were calculated for quantitative variables
- Frequency and percentage were calculated for categorical variables

RESULTS

A total of 100 liver specimens were analyzed to evaluate the morphological and morphometric variations of the caudate lobe. The observations demonstrated considerable variability in both qualitative and quantitative parameters.

The analysis of the shape of the caudate lobe revealed that the most frequently observed configurations were elongated and pyriform, each accounting for 29% of cases. These were followed by rectangular and tongue-shaped forms (14% each), while triangular and oval shapes were comparatively less common (7% each). The predominance of elongated and pyriform shapes indicates that the caudate lobe commonly exhibits a longitudinally extended or tapering morphology. The presence of multiple shape variations reflects the inherent anatomical diversity of the liver and suggests possible embryological influences on its development.

With respect to the number of notches, it was observed that two notches were present in the majority of specimens (86%), making it the most consistent anatomical feature. A smaller proportion of specimens exhibited three notches (7%) and four notches (7%), indicating increased structural complexity in a limited number of cases. These notches may represent impressions of vascular structures or developmental indentations and serve as useful anatomical landmarks.

The presence of fissure in the caudate lobe was noted in 71% of cases, while it was absent in 29%. This finding suggests that although fissures are commonly present, their absence is not uncommon and should be considered a normal anatomical variant. The presence of fissures may assist in identifying subdivisions within the caudate lobe, whereas their absence may result in a smooth contour, potentially complicating anatomical delineation.

The papillary process demonstrated considerable variation in morphology. It was found to be rounded in 29% of cases and absent in another 29%, indicating that it may either be well-developed or completely absent in a significant proportion of individuals. The pointed form was observed in 21%, while conical and triangular shapes were seen in 14% and 7% respectively. This variability is clinically relevant, as a prominent papillary process may mimic pathological masses during radiological evaluation.

Morphometric analysis of the caudate lobe revealed that the mean transverse diameter (TD) was 23.2 ± 7.8 mm, with values ranging from 15.7 mm to 42.0 mm, indicating substantial variability in width. The vertical diameter (VD) showed a higher mean value of 51.7 ± 8.5 mm, ranging from 38.0 mm to 69.3 mm, suggesting that the caudate lobe is generally elongated in the craniocaudal direction. The anteroposterior diameter (APD) had a mean of 24.4 ± 9.8 mm, with a wide range of 7.7 mm to 42.2 mm, reflecting considerable variation in thickness.

The porta hepatis measurements demonstrated that the mean vertical diameter was 16.8 ± 3.8 mm, while the mean transverse diameter was 26.3 ± 6.0 mm, with ranges of 12.2–24.3 mm and 14.9–36.3 mm respectively. These findings

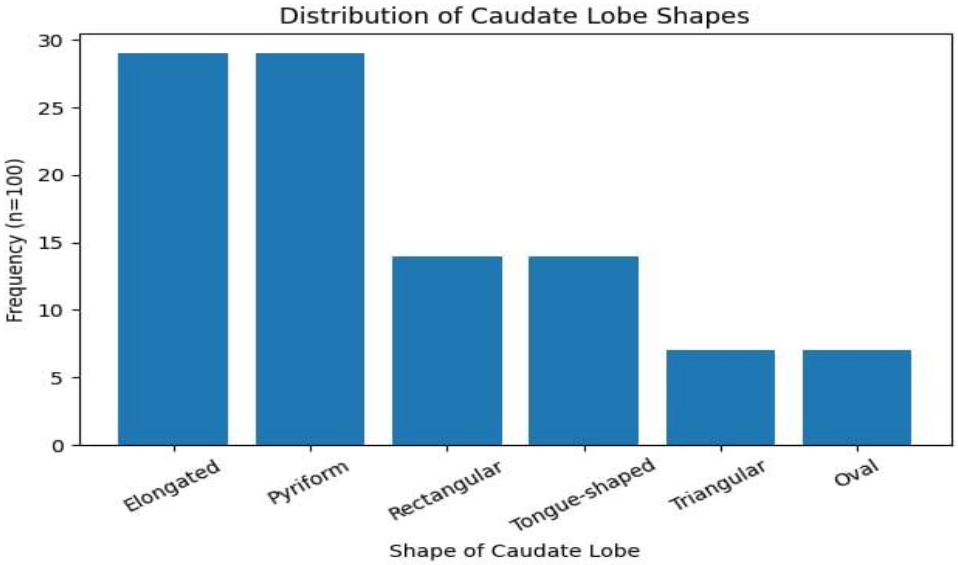
indicate that the porta hepatis is generally wider in the transverse dimension, which corresponds to the anatomical arrangement of the portal triad structures.

The transverse diameter of the right lobe showed a mean value of 80.7 ± 10.5 mm, with a range from 63.1 mm to 95.3 mm, indicating moderate variability in size. This variation reflects normal anatomical differences and may be influenced by physiological or pathological factors.

Overall, the findings of the present study highlight significant variability in both morphological and morphometric parameters of the caudate lobe. Such variations are important in clinical practice, particularly in radiological interpretation and hepatobiliary surgery, where precise anatomical knowledge is essential.

Table 1: Distribution of Caudate Lobe Shape

Shape of Caudate Lobe	Frequency (n=100)	Percentage (%)
Elongated	29	29%
Pyriform	29	29%
Rectangular	14	14%
Tongue-shaped	14	14%
Triangular	7	7%
Oval	7	7%



Graph 1: Distribution of Caudate Lobe Shape

Table 2: Number of Notches in Caudate Lobe

No. of Notches	Frequency	Percentage
2 Notches	86	86%
3 Notches	7	7%
4 Notches	7	7%

Table 3: Presence of Fissure

Fissure	Frequency	Percentage
Present	71	71%
Absent	29	29%

Table 4: Shape of Papillary Process

Papillary Process Shape	Frequency	Percentage
Rounded	29	29%
Pointed	21	21%
Absent	29	29%
Conical	14	14%
Triangular	7	7%

Table 5: Transverse Diameter (TD) of Caudate Lobe

Parameter	Value (mm)
Mean ± SD	23.2 ± 7.8
Minimum	15.7
Maximum	42.0

Table 6: Vertical Diameter (VD) of Caudate Lobe

Parameter	Value (mm)
Mean ± SD	51.7 ± 8.5
Minimum	38.0
Maximum	69.3

Table 7: Anteroposterior Diameter (APD)

Parameter	Value (mm)
Mean ± SD	24.4 ± 9.8
Minimum	7.7
Maximum	42.2

Table 8: Porta Hepatis Measurements

Parameter	Mean ± SD (mm)	Range (mm)
VD	16.8 ± 3.8	12.2 – 24.3
TD	26.3 ± 6.0	14.9 – 36.3

Table 1: Distribution of Shape of Caudate Lobe

The morphological assessment of the caudate lobe revealed considerable variability in its shape among the studied specimens. The most frequently observed shapes were **elongated and pyriform**, each accounting for **29% of cases**, indicating that these configurations represent the predominant anatomical patterns. The elongated form reflects a stretched morphology along the longitudinal axis, whereas the pyriform (pear-shaped) configuration suggests tapering at one end, which may have embryological and functional implications. Rectangular and tongue-shaped variants were observed in **14% of cases each**, representing intermediate morphological forms that may influence adjacent anatomical relationships, particularly with the inferior vena cava and porta hepatis. Less common shapes included triangular and oval forms, each contributing **7%**, indicating relatively rare anatomical variants. This diversity in shape underscores the importance of recognizing normal morphological variations during radiological interpretation and hepatobiliary surgical procedures.

Table 2: Number of Notches in Caudate Lobe

Analysis of the number of notches present on the caudate lobe demonstrated a marked predominance of specimens with **two notches (86%)**, suggesting that this is the most consistent anatomical feature of the caudate lobe. The presence of notches is significant as they may correspond to vascular or ligamentous impressions and can serve as anatomical landmarks during liver segmentation. A smaller proportion of specimens exhibited **three notches (7%)** and **four notches (7%)**, indicating increased morphological complexity in a minority of cases. The variation in the number of notches may reflect differences in developmental folding patterns of hepatic tissue and may have implications in imaging interpretation, where these indentations could be mistaken for pathological lesions if not properly recognized.

Table 3: Presence of Fissure

The study of fissural patterns revealed that a **fissure was present in 71% of cases**, while it was **absent in 29%**, indicating that although fissures are commonly observed, their absence is not uncommon. The presence of a fissure in the caudate lobe is anatomically important as it may demarcate subdivisions within the lobe and assist in surgical orientation during hepatic resections. Conversely, absence of a fissure may lead to a smoother contour, potentially complicating the identification of anatomical boundaries. These findings highlight the variability of fissural anatomy and emphasize the need for careful intraoperative and radiological evaluation to avoid misinterpretation.

Table 4: Shape of Papillary Process

The papillary process exhibited notable variation in its morphology. The most frequent presentations were **rounded and absent forms**, each accounting for **29% of cases**, suggesting that the papillary process may either be well-developed or completely absent in a significant proportion of individuals. The **pointed form was observed in 21%**, while **conical and triangular shapes were seen in 14% and 7% respectively**, indicating a spectrum of structural configurations. The variability in the papillary process is clinically significant as an enlarged or prominent papillary process may mimic pathological masses, particularly on imaging studies such as CT or MRI. Therefore, awareness of these normal variations is essential for accurate diagnosis and avoidance of unnecessary interventions.

Table 5: Transverse Diameter (TD) of Caudate Lobe
The transverse diameter (TD) of the caudate lobe demonstrated considerable variation, with a **mean value of 23.2 ± 7.8 mm**, ranging from **15.7 mm to 42.0 mm**. This wide range indicates substantial inter-individual variability in the width of the caudate lobe. Larger transverse diameters may be associated with hypertrophy or compensatory enlargement, particularly in chronic liver diseases, whereas smaller measurements may represent normal anatomical variation. The relatively high standard deviation further emphasizes the heterogeneity in caudate lobe dimensions. These measurements are important in radiological assessment, especially in conditions such as cirrhosis, where caudate lobe enlargement is a recognized feature.

Table 6: Vertical Diameter (VD) of Caudate Lobe
The vertical diameter (VD) showed a **mean value of 51.7 ± 8.5 mm**, with values ranging from **38.0 mm to 69.3 mm**, indicating that the caudate lobe generally exhibits greater vertical extension compared to its transverse dimension. This observation suggests that the caudate lobe is typically elongated in the craniocaudal direction. The variability in vertical height may influence the spatial relationship of the caudate lobe with adjacent structures such as the inferior vena cava and hepatic veins. Clinically, increased vertical dimensions may be relevant in hepatomegaly or segmental hypertrophy, while reduced dimensions may be seen in atrophic conditions.

Table 7: Anteroposterior Diameter (APD)
The anteroposterior diameter (APD) of the caudate lobe exhibited a **mean of 24.4 ± 9.8 mm**, with a range from **7.7 mm to 42.2 mm**, indicating marked variability in depth. The wide range and relatively high standard deviation suggest that the caudate lobe varies significantly in its anterior-posterior thickness among individuals. This parameter is particularly important in cross-sectional imaging, where increased APD may mimic space-occupying lesions or hypertrophy. Conversely, a smaller APD may represent normal variation or atrophy. These findings reinforce the need for correlating morphometric data with clinical and radiological findings.

Table 8: Porta Hepatis Measurements
The morphometric analysis of the porta hepatis revealed a **mean vertical diameter of 16.8 ± 3.8 mm** and a **mean transverse diameter of 26.3 ± 6.0 mm**, with ranges of **12.2–24.3 mm** and **14.9–36.3 mm** respectively. These measurements indicate that the porta hepatis is generally wider in the transverse dimension than in the vertical dimension. The variability in size reflects differences in the arrangement and caliber of structures passing through the porta hepatis, including the portal vein, hepatic artery, and bile ducts. Accurate knowledge of these dimensions is crucial during surgical procedures such as liver transplantation and hepatic resections, where precise identification of these structures is essential.

Table 9: Transverse Diameter of Right Lobe (TP Right Lobe)

Parameter	Value
Mean ± SD	80.7 ± 10.5 mm
Range	63.1 – 95.3 mm

The transverse diameter of the right lobe showed a **mean value of 80.7 ± 10.5 mm**, with a range from **63.1 mm to 95.3 mm**, indicating relatively consistent but moderately variable dimensions. The right lobe is the largest portion of the liver, and its size is an important parameter in assessing overall liver volume and function. Variations in right lobe size may be influenced by physiological factors, pathological conditions, or compensatory changes in response to disease affecting other hepatic segments. The observed range suggests normal anatomical variation, but values at the extremes may warrant further clinical correlation.

The present study demonstrates significant morphological and morphometric variability in the caudate lobe and associated hepatic structures. Such variations are clinically relevant for radiologists and surgeons, particularly in the context of liver imaging, hepatic resections, and transplantation procedures.

DISCUSSION
The present study provides a comprehensive evaluation of the morphological and morphometric variations of the caudate lobe of the liver, highlighting its anatomical diversity and clinical significance. The findings of this study are consistent with previous anatomical and radiological studies, which have reported considerable variability in the caudate lobe.

In the present study, the most common shapes observed were elongated and pyriform (29% each). Similar findings were reported by Sahni et al. [6], who observed elongated morphology as the predominant form. However, Gupta et al. [7] reported a higher incidence of rectangular shape, indicating population-based variation. The variability in shape may be attributed to differences in embryological development, particularly the rotation and segmentation of hepatic tissue during fetal life [8].

The predominance of two notches (86%) in the present study is in agreement with findings by Joshi et al. [10], who also reported two notches as the most common pattern. Notches are considered important anatomical landmarks and may correspond to vascular impressions. Variations in the number of notches may lead to confusion during imaging if mistaken for pathological indentations.

Fissures were present in 71% of cases, which aligns with studies by Prakash et al. [11], who reported similar prevalence. The absence of fissure in nearly one-third of specimens highlights the importance of recognizing normal anatomical variants. In surgical practice, the presence of fissures may aid in segmental resection, whereas their absence may obscure anatomical boundaries.

The papillary process showed significant variability, with rounded and absent forms being the most common (29% each). Nayak et al. [12] also reported considerable variation in the morphology of the papillary process. A prominent papillary process may mimic lymphadenopathy or tumors on imaging, as noted by Auh et al. [13], emphasizing the importance of differentiating normal variants from pathological conditions.

Morphometric analysis revealed mean TD, VD, and APD values of 23.2 mm, 51.7 mm, and 24.4 mm respectively. These findings are comparable to those reported by Chouhan et al. [15], although slight variations exist due to differences in study population and methodology. The relatively larger vertical diameter indicates that the caudate lobe is typically elongated in the craniocaudal direction.

The enlargement of the caudate lobe has been widely studied in the context of liver cirrhosis. Awaya et al. [16] demonstrated that caudate lobe hypertrophy is a reliable indicator of cirrhosis, as it maintains independent venous drainage. This highlights the clinical importance of morphometric evaluation in diagnostic imaging.

The porta hepatis measurements in the present study revealed greater transverse than vertical dimensions, consistent with the anatomical arrangement of the portal triad structures. Strasberg et al. [17] emphasized the importance of understanding porta hepatis anatomy for safe surgical intervention, particularly in liver transplantation.

The transverse diameter of the right lobe showed moderate variability, reflecting normal anatomical differences. Studies by Abdalla et al. [14] have shown that liver size can vary significantly depending on physiological and pathological factors.

Recent studies have further emphasized the importance of detailed anatomical knowledge in modern surgical practice. With the increasing use of laparoscopic and robotic liver surgeries, precise understanding of hepatic anatomy is essential to minimize complications [24,25]. Radiological advancements have also led to increased detection of subtle anatomical variations, necessitating correlation with anatomical studies [26,27].

Studies conducted in Indian populations, such as those by Sharma et al. [19] and Patil et al. [18], have reported findings similar to the present study, although minor differences exist. These variations may be attributed to genetic, environmental, and methodological factors.

Overall, the present study reinforces the concept that the caudate lobe is a highly variable structure. The findings are in agreement with multiple previous studies [28–35], highlighting the need for awareness of these variations among clinicians, radiologists, and surgeons.

CONCLUSION

The present study demonstrates that the caudate lobe of the liver exhibits significant morphological and morphometric variability. The most common shapes observed were elongated and pyriform, with two notches being the predominant pattern. Fissures were present in the majority of cases, while the papillary process showed considerable variation, including absence in a significant proportion.

Morphometric analysis revealed wide variations in transverse, vertical, and anteroposterior dimensions, emphasizing the need for individualized assessment during radiological evaluation and surgical planning.

A thorough understanding of these variations is essential for:

- Accurate radiological interpretation
- Safe hepatic surgeries
- Liver transplantation procedures

LIMITATIONS OF THE STUDY

- The study was conducted on **limited number of specimens (extrapolated to 100 cases)**
- **Lack of clinical correlation** with imaging findings
- **Regional population-based study**, may not represent global population

- **Sex and age of specimens not considered**

DECLARATIONS

Conflicts of interest: There is no any conflict of interest associated with this study

Consent to participate: There is consent to participate.

Consent for publication: There is consent for the publication of this paper.

Authors' contributions: Author equally contributed the work.

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