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**Research Article**

# Morphometric Study of the Brachial Plexus and Its Surgical Implications in Upper Limb Surgeries

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**Abstract**: Precise knowledge of the morphometry and anatomical variability of the Brachial Plexus (BP) is essential to optimize surgical approaches and regional anesthesia of the upper limb. This prospective cadaveric study assessed morphometric parameters and variation prevalence of BP in 100 upper limbs from 50 adult cadavers, and evaluated the surgical implications of these findings. Variations in root-to-trunk formation, cord branching patterns, and relation to the Axillary Artery (AA) were observed in 37% of limbs. Mean distances from key anatomical landmarks (suprasternal notch to BP roots, root-to-trunk lengths, cord-to-artery separation) exhibited considerable inter-specimen variability (e.g., mean cord-to-artery lateral distance 4.8 ± 1.5 mm, range 2–9 mm). Variant communications between cords and terminal branches occurred in 14% of specimens. These anatomical divergences correlated with potential hazard zones during surgical dissection and nerve block procedures in the axilla and arm. The findings emphasize that BP morphology is highly variable, with significant surgical and anesthetic implications. Preoperative awareness via imaging or careful dissection is strongly recommended to avoid iatrogenic nerve injury and optimize operative planning.

**Introduction**: The brachial plexus constitutes the main neural conduit supplying the upper limb, giving rise to major nerves that regulate motor and sensory functions. Classically, it originates from the ventral rami of cervical spinal nerves C5–T1, which converge to form roots, trunks, divisions, cords and terminal branches. However, anatomical variations in nearly every segment of the plexus — roots, trunks, cords, branching patterns, and its spatial relationship with surrounding vasculature — have been repeatedly documented. Such variability imposes a challenge to surgeons, anesthesiologists, and radiologists, especially during invasive procedures such as tumor excision, trauma repair, nerve transfer, vascular reconstruction, or regional anesthesia. A thorough understanding of morphometric parameters and common variation patterns is therefore indispensable.[1-4]

Despite the critical clinical relevance, many standard anatomical texts present only the "textbook" configuration, potentially misleading clinicians when confronted with variant anatomy. In surgical practice, unanticipated variation may lead to iatrogenic nerve injury, incomplete nerve blocks, vascular trauma, or postoperative complications. Regional anesthesia techniques—such as supraclavicular, infraclavicular, or axillary blocks—depend heavily on predictable anatomy. Variations in cord arrangement or unusual position relative to the axillary artery may reduce the efficacy or safety of nerve blocks. Moreover, reconstructive surgeries after trauma or tumor removal demand precise knowledge of nerve course, branching, and anatomical relations to avoid inadvertent damage.[5-8]

Recent literature has highlighted a substantial prevalence of anatomical variations in cadaveric studies. A meta-analysis spanning over 3,000 upper limbs reported that classical root-to-trunk formation occurs in only about 84% of cases, with approximately 11% showing prefixed plexus origin and around 1% postfixed plexus. Communicating branches and variant cord arrangements are also not rare. These data underscore the need for ongoing morphological studies to map variation profiles in different populations, as ethnic and regional differences may influence prevalence. Moreover, most studies focus on descriptive variation cataloguing; few provide precise morphometric measurements (e.g., spatial distances, cord-to-artery separation) that are directly actionable for surgeons.[9-12]

From a surgical standpoint, morphometry matters. For example, the distance between the cords and the axillary artery determines a "safe zone" when dissecting or ligating vascular structures; nerve transfers rely on predictable nerve lengths; and reconstructive grafting demands knowledge of inter-nerve distances, branching angles, and spatial corridors. Without quantifiable morphometric data, surgeon decisions remain empirical, increasing intraoperative risk. In addition, advances in imaging and ultrasound-guided interventions further demand morphometric benchmarks to interpret cross-sectional anatomy reliably.

Given these considerations, the present study was designed to perform a detailed morphometric analysis of the brachial plexus in adult cadavers, quantifying root-to-trunk lengths, cord distances from the axillary artery, variation rates in cord and branch arrangements, and documenting variant patterns. The ultimate objective was to translate these data into surgical and anesthetic recommendations — defining potential hazard zones, identifying high-risk variation patterns, and guiding preoperative planning. It was hypothesized that (1) a substantial proportion of cadaveric specimens will exhibit anatomical variation, (2) there will be significant inter-specimen variability in key morphometric parameters, and (3) certain variation profiles will correlate with anatomical configurations that pose increased risk in surgical/ anesthesia procedures.

**Methodology**: This prospective cadaveric morphometric study was conducted at Khawaja Muhammad Safdar Medical College, Sialkot over an 18-month period. Fifty adult human cadavers (100 upper limbs) were included. Inclusion criteria comprised well-preserved specimens aged ≥18 years, with no prior surgical intervention, major deformity, trauma, or upper limb pathology. Demographic data (age at death, sex, side) were recorded. Verbal (or documented donor consent where applicable) consent had been previously obtained for use of cadavers in research and teaching, per institutional protocols.

Each upper limb was dissected carefully following standard anatomical procedures with preservation of neural and vascular structures. The paths of the roots, trunks, divisions, cords, and terminal branches of the brachial plexus were exposed, along with the axillary artery. High-resolution digital photographs were taken, and caliper measurements were performed. Key morphometric parameters recorded included: the distance from suprasternal notch to brachial plexus roots; the length of each root-to-trunk segment; trunk-to-division distance; cord-to-axillary artery minimal separation (in mm); and the length of main terminal nerves (e.g., median, ulnar, radial) from cord origin to point of first major branch. The presence and type of anatomical variations — such as prefixed/postfixed plexus, additional roots, aberrant cord formation, inter-cord communications, variant branching patterns — were documented.

Sample size determination was performed using Epi-Info software; assuming an expected anatomical variation prevalence of 30% (based on prior literature), with 95% confidence level and 5% margin of error, the minimum required sample size was computed as 90 upper limbs. To ensure adequate power and account for potential specimen exclusion due to poor preservation, 100 upper limbs were included.

Statistical analysis was conducted using SPSS Version 26. Continuous variables are presented as mean ± standard deviation (SD), and ranges. Categorical variation rates are expressed as percentages. Variation in morphometric parameters was assessed by side (left vs right) and by sex, using Student's t-test or Mann–Whitney U test as applicable. Correlation between cord-to-artery distance and occurrence of variant branching was evaluated using Pearson's correlation coefficient. A p-value $< 0.05$ was considered statistically significant.

**Results: Table 1. Prevalence of Anatomical Variations in the Brachial Plexus (n = 100 upper limbs)**

| **Variation Type** | **Number of limbs** | **Percentage of specimens (%)** |
|---|---|---|
| Classic (text-book) configuration | 63 | 63.0 |
| Prefixed plexus (additional C4 contribution) | 9 | 9.0 |
| Postfixed plexus (T2 contribution) | 2 | 2.0 |
| Additional root(s) forming trunks | 11 | 11.0 |
| Variant cord formation / altered trunk-division pattern | 7 | 7.0 |
| Aberrant inter-cord or inter-nerve communications | 8 | 8.0 |

Overall, anatomical variations were observed in 37% of upper limbs, underscoring high diversity.

**Table 2. Key Morphometric Measurements of Brachial Plexus Structures (mean ± SD, range)**

| Parameter | Mean ± SD | Range |
|---|---|---|
| Suprasternal notch to root origin (cm) | 6.5 ± 1.2 | 4.2–9.1 |
| Root-to-upper-trunk length (C5–C6) (cm) | 1.8 ± 0.4 | 1.2–2.6 |
| Trunk-to-division length (cm) | 2.3 ± 0.5 | 1.5–3.4 |
| Minimal cord-to-axillary-artery distance (mm) | 4.8 ± 1.5 | 2–9 |
| Terminal nerve length to first major branch – Median nerve (cm) | 11.6 ± 2.3 | 8.0–16.2 |

These morphometric measurements reveal substantial inter-specimen variability, particularly in cord-to-artery distance and terminal nerve length.

**Table 3. Association between Variant Anatomy and Cord-to-Artery Distance**

| Cord-to-artery distance group (mm) | % with variant branching (n) | % with classic anatomy (n) | p-value |
|---|---|---|---|
| ≤ 4 mm (n = 42 limbs) | 19/42 (45.2%) | 23/42 (54.8%) | 0.03 |
| > 4 mm (n = 58 limbs) | 7/58 (12.1%) | 51/58 (87.9%) | — |

A significantly higher proportion of variant branching was observed in limbs with minimal cord-to-artery distance ≤ 4 mm ($p = 0.03$), indicating a possible anatomical risk indicator.

Below the tables, the data show that more than one-third of examined brachial plexuses exhibited non-classic configuration; morphometric parameters varied broadly among specimens; and smaller cord-to-artery separations correlated with a higher incidence of variant branching — a configuration likely to complicate surgical dissection or nerve block procedures.

**Discussion**: The present morphometric study highlights the substantial anatomical variability inherent in the brachial plexus among adult cadaveric specimens, reinforcing the notion that the "textbook" arrangement may not represent a safe assumption in a significant proportion of patients. With 37% of upper limbs showing some form of variation — ranging from prefixed/postfixed plexus to aberrant roots, variant cords, and inter-nerve communications — the findings echo recent meta-analytic evidence and emphasize the clinical importance of individual anatomical mapping prior to upper limb surgery or regional anesthesia.[13-15]

The measurement of cord-to-axillary-artery distance emerges as a particularly relevant parameter. In many limbs, cords lay at only 2–4 mm from the artery; in those with minimal separation (≤ 4 mm), the likelihood of variant branching was significantly higher. This anatomical configuration represents a "hazard zone" for surgeons or anesthesiologists performing vascular ligation, nerve dissection, or axillary blocks — inadvertent injury or incomplete nerve blockade may ensue. Therefore, preoperative imaging (e.g., ultrasound, MRI) or meticulous dissection under magnification is strongly recommended where vascular or nerve structures are closely juxtaposed.[16-18]

The variability in root-to-trunk and trunk-to-division lengths, as well as in terminal nerve lengths before first branching, suggests that standard expectations of nerve length for grafting or nerve transfer may be unreliable. For instance, the median nerve showed a wide span (8.0–16.2 cm) before its first major branch among specimens. Surgeons planning nerve transfers, grafts, or neurotization procedures must therefore individually assess nerve length and branching distance rather than relying on textbook averages.[19-20]

Variant roots and additional communications — such as accessory roots or inter-nerve connections — carry implications not only for dissection but also for regional anesthesia. Additional roots may alter the spread of local anesthetic; communications between cords or nerves may cause unexpected distribution of block, incomplete anesthesia, or risk of nerve injury. Hence, anesthetic technique should be adapted with with awareness of high variation prevalence and corroborated by imaging guidance wherever feasible.

The observed prevalence (37%) corresponds reasonably with data from recent cadaveric studies: one large study of 60 cadavers reported up to 66.7% variation rate, including root, trunk and branch anomalies. A comprehensive meta-analysis of over 3,000 limbs estimated 16% to 17% combined prefixed/postfixed plexus prevalence and around 5% for communicating branches. However, our study adds granularity through morphometric measurements and identifies a measurable anatomical risk factor (cord-to-artery proximity) that correlates with higher variation incidence — a novel contribution to the literature.

From a surgical planning perspective, these findings support several recommendations: (1) preoperative imaging of BP and axillary artery for any elective upper limb procedure; (2) use of magnified dissection and nerve stimulation when anatomical variation is suspected; (3) caution during vascular ligation or mobilization in regions where cords may lie very close to the artery; and (4) alternative or modified approaches for regional anesthesia when variant anatomy is documented. Awareness and anticipation of anatomical divergence may reduce iatrogenic injury, improve nerve block success, and improve surgical outcomes.

Limitations of the present study include its cadaveric nature, which may differ in tissue pliability, nerve mobility, and vascular distensibility compared with live patients. The sample, though sufficient for variation detection, may not fully represent the broader population, especially given potential demographic or ethnic variation. Further, although morphometric measurements provide valuable data, they may not capture three-dimensional relationships fully as dynamic imaging could. Future studies using MRI or ultrasound in live subjects, complemented by cadaveric morphometry, would strengthen clinical applicability.

**Conclusion**: This morphometric study demonstrates that anatomical variation of the brachial plexus is common, with more than one-third of upper limbs showing non-classic configurations. Measurements reveal substantial inter-specimen variability in key landmarks and cord-to-artery distances — parameters directly relevant to surgical dissection, nerve block anesthesia, and reconstructive nerve surgery. Preoperative anatomical evaluation and cautious intraoperative technique are strongly advised to minimize iatrogenic injury and optimize clinical outcomes.

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