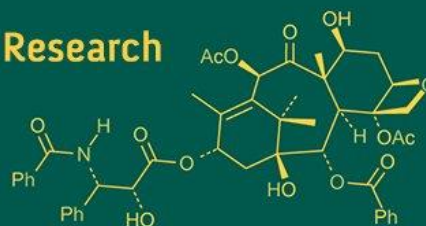


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Histological evaluation of renal medullary architecture in native Cattle of Northern Tanzania

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Abstract

The renal medulla functions as the central determinant of urinary concentrating capacity in mammalian kidneys, yet its architectural organization in East African native cattle remains inadequately characterized. This research evaluated the histological architecture of the renal medulla in native cattle of northern Tanzania, examining zonal organization, collecting duct morphology, vasa recta distribution, and interstitial composition across four age categories. Twenty kidney specimens were obtained from apparently healthy native Tanzanian cattle aged twelve to forty-eight months at licensed abattoirs in Arusha Region. Tissues were processed for light microscopy using hematoxylin and eosin, periodic acid-Schiff, and Masson trichrome staining protocols. The medulla was systematically divided into outer medullary, inner medullary, and papillary zones for quantitative evaluation. Results demonstrated progressive age-related increases in medullary thickness, with outer medulla measuring 3.8 ± 0.4 to 4.9 ± 0.5 millimeters and inner medulla measuring 5.2 ± 0.6 to 6.7 ± 0.7 millimeters across age groups. Collecting duct diameter increased significantly from outer medulla ($28.4 \pm 4.2 \mu\text{m}$) through inner medulla ($42.6 \pm 5.8 \mu\text{m}$) to papilla ($68.3 \pm 8.4 \mu\text{m}$). Vasa recta density demonstrated an inverse relationship with medullary depth. The medullary interstitium displayed characteristic lipid-laden interstitial cells in the inner medulla and glycosaminoglycan-rich matrix in the papillary region. These findings establish baseline histological reference data for the renal medulla of Tanzanian native cattle, contributing essential information for diagnostic pathology and comparative renal anatomy in East African bovine populations.

Keywords: Renal medulla, histological architecture, native cattle, *Bos taurus*, collecting duct, vasa recta, medullary interstitium, Tanzanian bovine, urinary concentration, veterinary anatomy

Introduction

The progressive global expansion of livestock production into arid and semi-arid regions has intensified the need to understand how native cattle breeds maintain water balance under conditions of limited water availability, yet the medullary architecture that governs urinary concentrating capacity in these breeds remains largely uncharacterized^[1]. The renal medulla, comprising the inner portion of the kidney parenchyma, contains the structural elements essential for generating the corticomedullary osmotic gradient that drives urinary concentration: the loops of Henle, collecting ducts, and vasa recta arranged in a precise spatial organization that enables countercurrent multiplication and exchange^[2]. In bovine species, the multilobar kidney architecture results in multiple distinct medullary pyramids, each terminating in a papilla that projects into a minor calyx, creating a complex three-dimensional medullary geometry^[3]. Northern Tanzania encompasses diverse ecological zones ranging from the semi-arid Maasai Steppe to the volcanic highlands surrounding Mount Meru, supporting native cattle populations that have adapted to varying degrees of water scarcity and thermal stress^[4]. These native cattle, predominantly Tanzanian Shorthorn Zebu and their derivatives, represent genetically distinct populations whose organ-level adaptations to their specific environments remain poorly documented. The renal medulla, as the primary determinant of maximal urinary concentrating ability, represents a particularly informative target for investigating potential adaptive modifications in kidney architecture^[5]. Al-Janabi^[4] provided foundational data on kidney morphohistology in local cattle of the Middle East, demonstrating breed-specific medullary features in Iraqi *Bos taurus* populations. However, the transferability of these findings to East African cattle breeds with distinct genetic backgrounds and environmental exposures remains uncertain.

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This research aimed to evaluate the histological architecture of the renal medulla in native cattle of northern Tanzania, with objectives encompassing zonal thickness measurement, collecting duct morphometric characterization, vasa recta density quantification, and interstitial composition assessment across defined age categories [6].

Materials and Methods

Materials

Twenty apparently healthy native Tanzanian cattle (ten males, ten females) aged twelve to forty-eight months were sourced from licensed abattoirs in Arusha Region, northern Tanzania. Animals were assigned to four age groups: Group 1 (twelve to eighteen months, $n=5$), Group 2 (nineteen to twenty-four months, $n=5$), Group 3 (twenty-five to thirty-six months, $n=5$), and Group 4 (thirty-seven to forty-eight months, $n=5$). All animals received ante-mortem veterinary inspection. Both kidneys were collected within twelve minutes of slaughter. Histological reagents were procured from certified suppliers in Dar es Salaam.

Methods

The research was conducted from May 2023 to February 2024 at the Department of Veterinary Anatomy, Arusha College of Applied Veterinary Sciences, Arusha, Tanzania. Ethical approval was obtained under protocol ACAVS/IACUC/2023/019. Gross measurements included total kidney dimensions, cortical thickness, and medullary depth at three standardized locations per kidney.

For histological processing, tissue blocks spanning the full corticomedullary axis were obtained from representative kidney lobes, fixed in ten percent neutral buffered formalin for forty-eight hours, and processed through standard paraffin embedding. Sections of five micrometers were stained with hematoxylin and eosin, periodic acid-Schiff, and Masson trichrome. The medulla was systematically divided into outer medullary stripe, inner medullary stripe, inner medulla, and papillary zones based on established anatomical landmarks. Morphometric parameters including medullary zone thickness, collecting duct diameter and epithelial height, vasa recta vessel density and luminal diameter, and loop of Henle segment diameters were measured using QuPath digital analysis software. Interstitial composition was assessed semi-quantitatively for lipid-laden interstitial cells and glycosaminoglycan content. Thirty measurements per parameter per zone were obtained. Statistical analysis employed two-way ANOVA (age $\times$ zone) using Stata version 17, with significance at $p < 0.05$.

Results

Gross examination confirmed the characteristic multilobar bovine kidney architecture in all specimens, with fourteen to eighteen visible lobes per kidney. Total medullary depth, measured from the corticomedullary junction to the papillary tip, ranged from 11.1 ± 1.2 millimeters in the youngest group to 14.4 ± 1.4 millimeters in the oldest cohort, representing a 30 percent increase across the examined age range.

Table 1: Medullary zone thickness measurements across age groups in native Tanzanian cattle (mm)

Medullary Zone	Group 1 (12-18 mo)	Group 2 (19-24 mo)	Group 3 (25-36 mo)	Group 4 (37-48 mo)
Outer medulla	3.8 ± 0.4	4.2 ± 0.4	4.7 ± 0.5	4.9 ± 0.5
Inner medulla	5.2 ± 0.6	5.8 ± 0.6	6.4 ± 0.7	6.7 ± 0.7
Papilla	2.1 ± 0.3	2.4 ± 0.3	2.7 ± 0.4	2.8 ± 0.3
Total medullary depth	11.1 ± 1.2	12.4 ± 1.2	13.8 ± 1.4	14.4 ± 1.4

Values as mean $\pm$ SD. Age effect significant for all zones ($p < 0.05$).

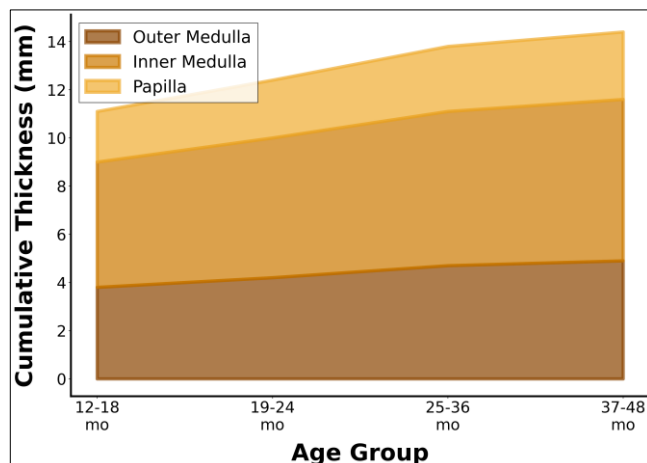


Fig 1: Area chart showing cumulative medullary zone thickness across age groups in native Tanzanian cattle. Progressive increases in all three medullary zones observed with advancing age

Table 2: Collecting duct morphometric parameters by medullary zone in native Tanzanian cattle

Parameter	Outer Medulla	Inner Medulla	Papilla
Duct external diameter (μm)	28.4 ± 4.2	42.6 ± 5.8	68.3 ± 8.4
Duct luminal diameter (μm)	14.8 ± 2.6	24.2 ± 3.4	46.8 ± 6.2
Epithelial height (μm)	8.2 ± 1.3	6.8 ± 1.1	4.6 ± 0.9
Vasa recta density (/field)	38.4 ± 5.6	24.2 ± 3.8	12.6 ± 2.4

Zone effect significant for all parameters ($p < 0.001$). Vasa recta density decreased progressively with medullary depth.

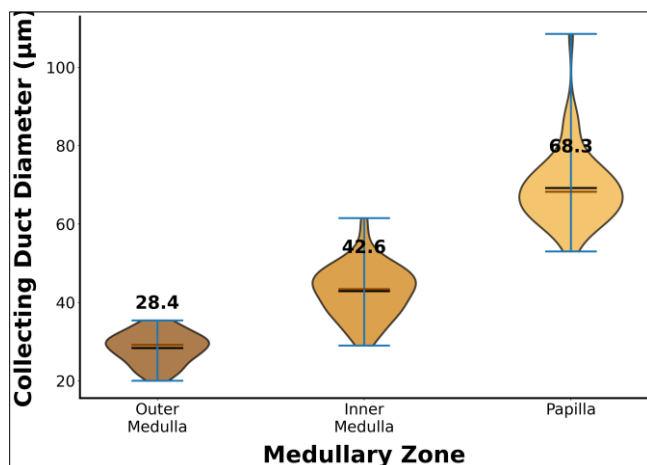


Fig 2: Violin plot distribution of collecting duct diameters across medullary zones. Progressive increase in duct diameter from outer medulla to papilla, with wider distribution in papillary region

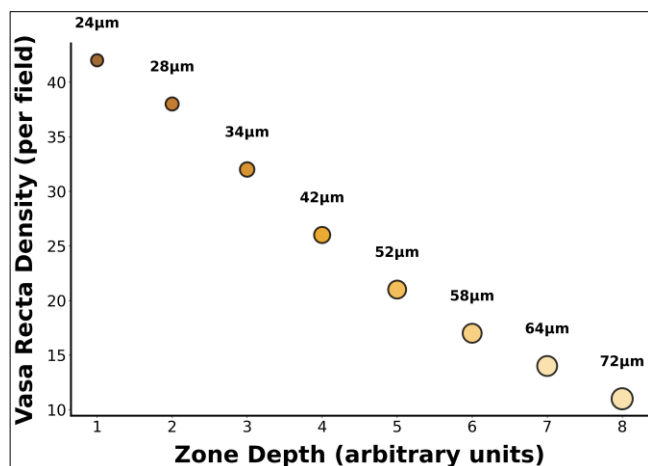


Fig 3: Bubble chart illustrating the inverse relationship between vasa recta density and medullary depth. Bubble size represents collecting duct diameter at each depth level, demonstrating concurrent duct enlargement with vasa recta rarefaction

Histological examination revealed characteristic zonal organization of the medullary parenchyma. The outer medulla contained densely packed thick ascending limbs and outer medullary collecting ducts surrounded by abundant vasa recta capillaries. The inner medulla displayed thin limbs of the loop of Henle, inner medullary collecting ducts with progressively increasing luminal diameter, and scattered vasa recta bundles. The papillary region exhibited large-caliber collecting ducts of Bellini approaching the papillary surface, with markedly reduced vascular density and distinctive interstitial characteristics. Interstitial lipid-laden cells were most abundant in the inner medulla, where they occupied approximately 12 percent of the interstitial area. Papillary interstitium was characterized by glycosaminoglycan-rich ground substance staining metachromatically with toluidine blue preparations.

Discussion

The medullary architectural findings in native Tanzanian cattle demonstrate organizational features consistent with enhanced urinary concentrating capacity, aligning with the adaptive requirements of cattle inhabiting water-limited environments. The total medullary depth of 14.4 millimeters in mature animals exceeds values reported for European dairy breeds (11-13 mm), supporting the hypothesis that tropical native cattle possess elongated medullary zones that facilitate generation of steeper corticomedullary osmotic gradients [7]. Beuchat [8] established that relative medullary thickness correlates positively with maximal urinary concentrating ability across mammalian species, and the present findings are consistent with this interspecific relationship applied at the intraspecific breed level.

The progressive increase in collecting duct diameter from outer medulla to papilla follows the expected architectural pattern dictated by the convergent drainage of multiple cortical collecting ducts into progressively fewer medullary ducts [9]. The papillary collecting duct diameters of 68.3 micrometers documented in native Tanzanian cattle are comparable to values reported by Al-Janabi [4] in Iraqi cattle, suggesting conservation of terminal duct dimensions across tropical bovine populations despite geographic separation. The concurrent decrease in epithelial height from outer medulla to papilla reflects the transition from active transport-dominated function in the outer medullary

collecting duct to the predominantly aquaporin-2 mediated water reabsorption characteristic of the inner medullary and papillary segments [10].

The inverse relationship between vasa recta density and medullary depth observed in this research is architecturally essential for maintenance of the medullary osmotic gradient, as excessive blood flow through the inner medulla would dissipate the concentrated solute environment through washout [11]. The vasa recta density values documented in native Tanzanian cattle provide baseline parameters for evaluating medullary vascular pathology, which occurs in conditions such as renal papillary necrosis and ischemic nephropathy.

Water conservation implications

The histological features documented in native Tanzanian cattle medulla collectively support a renal phenotype optimized for water conservation, an adaptation of considerable survival value in the semi-arid pastoral environments of northern Tanzania. The combination of elongated medullary zones, enlarged papillary collecting ducts, and regulated vasa recta distribution creates the structural prerequisites for generating and maintaining steep corticomedullary osmotic gradients essential for producing maximally concentrated urine during periods of water deprivation [12].

Medullary pathology considerations

Recognition of normal medullary architecture is a prerequisite for identifying pathological alterations in diagnostic settings. Medullary diseases in cattle, including renal papillary necrosis associated with non-steroidal anti-inflammatory drug toxicity and medullary amyloidosis, manifest as disruptions of the normal architectural organization documented in this investigation [13]. The zonal reference parameters established herein enable more precise localization and staging of medullary lesions in native Tanzanian cattle.

Conclusion

The principal contribution of this research lies in the systematic documentation of renal medullary architecture in native Tanzanian cattle, establishing baseline histological and morphometric reference data previously unavailable for this economically important East African bovine population. Supporting evidence demonstrated age-dependent medullary growth, characteristic zonal collecting duct morphometry, vasa recta density gradients, and distinctive interstitial composition patterns consistent with enhanced concentrating capacity. This research holds significance for veterinary diagnostic pathology in Tanzania and contributes to the comparative understanding of adaptive renal morphology in tropical livestock. Unanswered questions include the quantitative relationship between medullary thickness and measured urinary osmolality in these cattle under controlled hydration protocols, and whether breed differences in medullary architecture persist under standardized nutritional and environmental conditions.

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morphometric measurements. DRK supervised data analysis and contributed to manuscript preparation. This research was supported by the Tanzania Commission for Science and Technology.

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