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Histological and Cytoskeletal Specialization of the Infundibulum of the Camel Uterine Tube: Structural Adaptations for Reproductive Function

Especialización Histológica y Citoesquelética del Infundíbulo de la Tuba Uterina del Camello: Adaptaciones Estructurales para la Función Reproductiva

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SUMMARY: The infundibulum of the uterine tube provides a highly specialized microenvironment essential for oocyte capture, fertilization, and early embryonic development. In the dromedary camel (*Camelus dromedarius*), adaptation of this segment to environmental stress is mediated by coordinated structural and cytoskeletal modifications. However, the cellular basis of these adaptations remains insufficiently understood. This study investigated the histological organization, cytoskeletal protein distribution, and ultrastructural characteristics of the infundibulum. Tissue samples from nine adult non-pregnant camels were examined using routine histology, periodic acid–Schiff (PAS) histochemistry, immunohistochemistry for vimentin, desmin, and smooth muscle actin (SMA), and transmission electron microscopy. Histological results showed extensive hierarchical folding of the mucosa, lined by a simple columnar epithelium. This epithelium was composed of ciliated and secretory cells. Strong PAS reactivity in secretory cells was identified. Immunohistochemically, vimentin immunoreactivity was predominantly localized to non-ciliated epithelial cells and the vascular endothelium, supporting a role in epithelial stability and stromal organization. Desmin and SMA were strongly expressed in the tunica muscularis, with extensions into the cores of primary mucosal folds. Ultrastructurally, the secretory cells showed abundant rough endoplasmic reticulum, a prominent Golgi complex, and electron-dense granules. Ciliated cells contained numerous mitochondria, consistent with sustained ciliary activity. Apical cytoplasmic blebbing in secretory cells suggested an apocrine-like mode of secretion. In conclusion, the infundibulum of the camel oviduct shows coordinated changes in its lining cells and structural proteins, resulting in the integration of secretion, mechanical strength, and contractile areas. These structural features are likely important for successful reproduction under challenging environmental conditions.

KEY WORDS: *Camelus dromedarius*; **Infundibulum of uterine tube; Cytoskeletal remodeling; Epithelial specialization; Immunohistochemistry; Transmission electron microscopy.**

INTRODUCTION

The uterine tubes are a highly specialized region of the female reproductive tract. Their epithelium plays a critical role in secreting oviductal fluids, contributing to the formation of a dynamic microenvironment within this highly specialized region of the female reproductive tract, which is essential for gamete transport, fertilization, and early embryonic development (Katare *et al*., 2015). These processes are tightly regulated by coordinated ciliary activity and rhythmic smooth muscle contractions (Srikandakumar *et al*., 2011; Marettová & Maretta, 2014; Acuña *et al*., 2024; Juengel *et al*., 2024). In the dromedary camel (*Camelus dromedarius*), the uterine tube is divided into three distinct segments. These include the infundibulum, ampulla, and isthmus. Each segment contributes uniquely to reproductive success (Accogli *et al*., 2014; Mohey-Elsaeed *et al*., 2016; Runcan & da Silva, 2022).

Histologically, the uterine tube comprises mucosal, muscular, and serosal layers. The luminal epithelium is mainly composed of ciliated and secretory cells (Panyarachun *et al*., 2021). Species-specific structural variations have been reported. Notably, camels have a

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relatively thicker isthmus compared to bovine species (Salari *et al*., 2011). Prenatal studies have also shown early structural maturation of the infundibulum of the camel uterine tube. It is characterized by well-developed mucosal folds lined with pseudostratified epithelium (Oyelowo *et al*., 2021). Despite these observations, the functional implications of these structural adaptations, particularly in relation to environmental stress, remain poorly understood.

The cytoskeleton plays a fundamental role in maintaining tissue organization and supporting tubal function at the cellular level. Intermediate filaments (IFs), as key cytoskeletal components, provide mechanical stability, cellular integrity, and resilience to mechanical stress (Dey *et al*., 2014; Herrmann & Aebi, 2016). Vimentin is a mesenchymal IF. It contributes to structural support and cellular adaptability. Desmin is a muscle-specific IF. It is essential for the integrity and alignment of contractile elements. Smooth muscle actin (SMA) is a microfilament protein, not an IF, but it serves as a critical marker of smooth muscle differentiation and contractile activity (Eriksson *et al*., 2009; Clemen *et al*., 2013). Within the uterine tube, cytoskeletal components are closely associated with both epithelial organization and smooth muscle function. Desmin and SMA are integral to contractile activity within the muscular layer. Vimentin supports stromal architecture and enhances cellular resistance to mechanical stress (Marettová & Maretta, 2014; Hnia *et al*., 2015; Herrmann & Aebi, 2016). However, the spatial distribution and functional significance of these cytoskeletal proteins in the uterine tube of camel remain insufficiently characterized. Elucidating their localization is essential for understanding the mechanisms underlying motility of the uterine tube, epithelial stability, and reproductive efficiency.

The infundibulum is the rostral fimbriated segment of the uterine tube. It plays a critical role in capturing the ovulated oocyte and facilitating its entry into the uterine tube (Bosch & Wright, 2005; Abdelnaby *et al*., 2026). Existing histological descriptions of the uterine tube in camel exist (Accogli *et al*., 2014; Abdoon *et al*., 2024). Scanning electron microscopy studies have revealed regional epithelial specializations. These include apical surface modifications that may enhance gamete transport and fertilization (Accogli *et al*., 2014). Comprehensive ultrastructural investigations using transmission electron microscopy, however, remain limited, especially in this functionally important segment.

Studies integrating immunohistochemical localization of cytoskeletal proteins with detailed ultrastructural analysis are scarce, especially at the level of the infundibulum. Thus, the present study aimed to characterize the histological organization of the infundibulum of uterine tube in the dromedary camel. It also aimed to investigate the distribution of key cytoskeletal proteins, including vimentin, desmin, and SMA. In addition, ultrastructural features were examined using transmission electron microscopy. The focus was on epithelial specialization. By linking structural organization with cytoskeletal remodeling, this study provides new insights into uterine tube function and highlights potential adaptive features that support reproductive efficiency under environmental stress.

MATERIAL AND METHOD

Animals and tissue collection

Uterine tube samples were collected from nine clinically healthy, non-pregnant adult female dromedary camels, aged 7–10 years, slaughtered for human consumption at a local abattoir in Khartoum State, Sudan. Ovarian morphology was evaluated to confirm reproductive status before inclusion. Immediately after slaughter, the uterine tubes were excised. Samples from the infundibulum region were collected within a short post-mortem interval and promptly fixed in 10 % neutral buffered formalin for 24-48 h.

Ethical approval for this study was granted by the Research Council of the College of Veterinary Medicine, University of Bahri, Khartoum, Sudan. All procedures, including animal selection and tissue collection described above, were conducted in accordance with institutional guidelines for the use of animal tissues obtained from abattoirs.

General histology

Following fixation, tissues were dehydrated through ascending ethanol grades, cleared in xylene, and embedded in paraffin wax. Serial sections (4-5 μm) were prepared using a rotary microtome and stained with hematoxylin and eosin (H&E) for general histological evaluation, and periodic acid–Schiff (PAS) for the detection of neutral mucopolysaccharides, following standard protocols (Bancroft & Gamble, 2008).

Immunohistochemistry

Immunohistochemical staining was performed using the Biogenex Super Sensitive One-Step Polymer-HRP Detection System Kit (Emergo Europe, The Hague, The Netherlands). Paraffin-embedded sections (5 μm) were mounted on Superfrost Plus slides, deparaffinized in xylene, and rehydrated through graded ethanol to distilled water.

Table I. Primary and secondary antibodies used for immunohistochemistry.

Antibody	Manufacturer (Location, Country, Catalog No.)	Antibody type	Dilution	Incubation time
Mouse anti-vimentin	Dako Cytomation, Glostrup, Denmark (M7020)	Monoclonal primary antibody	1:200	1 hour
Mouse anti-smooth muscle actin	Dako Cytomation, Glostrup, Denmark (M0851)	Monoclonal primary antibody	1:50	1 hour
Mouse anti-desmin	Dako Cytomation, Glostrup, Denmark (M0760)	Monoclonal primary antibody	1:50	1 hour
Polymer-HRP detection system	Emergo Europe, The Hague, The Netherlands (HK59506K)	Secondary antibody (anti-mouse/anti-rabbit, HRP-linked polymer)	Ready-to-use	15 min

Endogenous peroxidase activity was blocked by incubation in 3 % hydrogen peroxide for 5 min. Sections were then rinsed in phosphate-buffered saline (PBS; 0.01 M, pH 7.4). Antigen retrieval was performed in citrate buffer (pH 6.0) using a microwave oven at 750 W for 3 cycles of 7 min each, followed by cooling at room temperature for 20 min.

Sections were incubated at room temperature with primary antibodies against vimentin, desmin, and smooth muscle actin (Table I). After washing in PBS, sections were incubated with the polymer-HRP detection reagent according to the manufacturer's instructions. Immunoreactivity was visualized using 3,3'-diaminobenzidine (DAB) as the chromogen, and sections were counterstained with Mayer's hematoxylin.

Negative controls were processed by omitting the primary antibody and replacing it with PBS, whereas positive controls consisted of tissues known to express the target antigens. Antibody specificity and cross-reactivity in camel tissues were verified by comparison with established mammalian controls.

Semi-quantitative evaluation of immunohistochemical staining was independently performed by three experienced observers. Staining intensity was classified as strong (+++), moderate (++), weak (+), or negative (-).

All stained sections were examined using a light microscope (Olympus BX63, Japan) equipped with a digital camera (Olympus DP72). Images were captured using CellSens 510 software.

Transmission electron microscopy

Tissue samples were sectioned into blocks of approximately 1 mm^3 and immediately fixed in 2.5 % glutaraldehyde prepared in 0.1 M sodium cacodylate buffer (pH 7.4) for 5 days (Bancroft & Stevens, 1996). This extended fixation period ensured adequate penetration and optimal preservation of ultrastructural details in the dense camel infundibulum tissue, thereby minimizing artifacts and enhancing image quality.

Following primary fixation, specimens were washed in 0.13 M Millonig's buffer (pH 7.2) for 10 min and post-fixed in 1 % osmium tetroxide in the same buffer for 1 h. Samples were then rinsed in distilled water and dehydrated through a graded ethanol series (50 %, 70 %, 80 %, 90 %, 95 %, and 100 %) for 10 min at each concentration. Dehydrated tissues were transferred to absolute ethanol and subsequently cleared in propylene oxide.

Specimens were infiltrated with epoxy resin using graded mixtures of propylene oxide and resin (2:1, then 1:2), and then embedded in fresh epoxy resin. Polymerization was performed overnight at 60 °C (Ayache *et al*., 2010).

Semi-thin sections (1 μm) were prepared using a glass knife and stained with buffered toluidine blue for light microscopic orientation. Ultra-thin sections (50–90 nm) were cut using an ultramicrotome (C. Reichert AG, Austria) equipped with a diamond knife and mounted on copper grids. Sections were stained with Reynolds' lead citrate and counterstained with uranyl acetate.

Ultrastructural analysis was performed using a transmission electron microscope (Philips, The Netherlands) operating at 80 kV. Digital images were captured using a MegaView III side-mounted camera (Olympus Soft Imaging Solutions GmbH, Münster, Germany) and processed with iTEM software to adjust brightness and contrast.

RESULTS

Histology

The infundibulum of the uterine tube of the dromedary camel exhibited a characteristic trilaminar organization, composed of the mucosa, tunica muscularis, and serosa (Fig. 1a). Extensive and complex folding characterized the mucosa. Deeply projecting into the

lumen, numerous irregular primary, secondary, and tertiary mucosal folds markedly increased the luminal surface area (Fig. 1a).

The mucosal epithelium consisted of simple columnar cells. These included both ciliated and non-ciliated (secretory) cell types. Ciliated cells possessed prominent apical cilia extending into the lumen. Non-ciliated cells exhibited dome-shaped apical protrusions indicative of secretory activity (Fig. 1b). Periodic acid–Schiff (PAS) staining revealed strong positive reactivity in non-ciliated cells. These cells contained abundant PAS-positive cytoplasmic granules. Ciliated cells displayed weak or negligible staining (Fig. 1b).

The lamina propria extended into the cores of the mucosal folds. It consisted of loosely arranged connective tissue containing numerous blood vessels (Fig. 1c). The tunica muscularis was composed of an inner circular layer and an outer longitudinal or variably oriented layer of smooth muscle fibers. A well-developed vascular connective tissue layer, the lamina vascularis, was interposed between these muscle layers. This layer contained blood vessels and interspersed smooth muscle fibers (Fig. 1d).

The outermost layer, the serosa, was thin and composed of loose connective tissue lined by mesothelium (Fig. 1a).

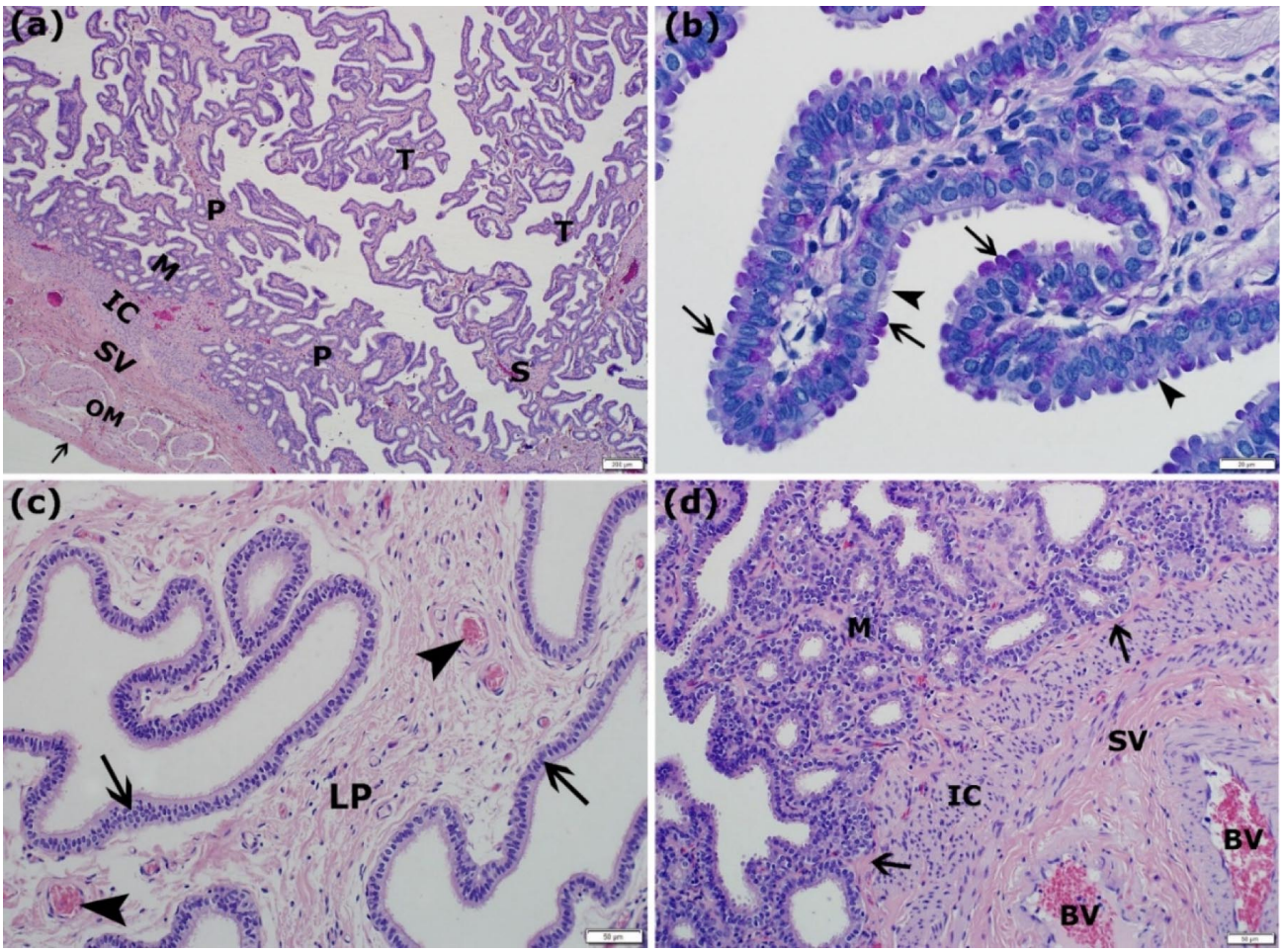


Fig. 1. Photomicrographs of the infundibulum of the tube uterine of dromedary camel. (a) General organization showing the tunica mucosa (M) with primary (P), secondary (S), and tertiary (T) mucosal folds, inner circular layer (IC) and outer muscular layer (OM) of the tunica muscularis, stratum vasculare (SV), and serosa (arrow). (b) Higher magnification of a tertiary mucosal fold lined by simple columnar epithelium composed of non-ciliated secretory cells with dome-shaped apical surfaces exhibiting strong PAS-positive reactions (arrows), and ciliated cells showing weak PAS reactivity (arrowheads). (c) Mucosal fold illustrating the epithelial lining (arrows) and lamina propria (LP) containing blood vessels (arrowheads). (d) Mucosal fold showing a thin lamina propria (arrow), inner circular smooth muscle layer (IC), and stratum vasculare (SV) with prominent blood vessels (BV). (a, c, d) Hematoxylin and eosin (H&E); (b) Periodic acid–Schiff (PAS).

Table II. Semi-quantitative evaluation of immunohistochemical reactivity of vimentin, desmin, and smooth muscle actin in the infundibulum of the camel oviduct.

Protein	Tunica muscularis		Tunica mucosa				
	SMF	TBV	CC	SC	LPF	LSF	LTF
Vimentin	-	+ ⁻	-/+	+++	+	-	-
Desmin	+++	++ ⁻	-	-	++	+	-
SMA	+++	+++/++⁻	-	-	+++/++	+	-

+++ strong reaction; ++ moderate reaction; + weak reaction; - negative reaction. CC: Ciliated cells; LPF: Lamina propria of primary fold; LSF: Lamina propria of secondary fold; LTF: Lamina propria of the tertiary fold; SC: Secretory cells; SMA: Smooth muscle actin; SMF: Smooth muscle fibres; TBV: Tunica media of blood vessels. ⁻ Endothelium of the blood vessels. ⁻ Tunica media of the blood vessels.

Immunohistochemistry

Semi-quantitative evaluation of immunoreactivity is presented in Table II.

Vimentin immunoreactivity was predominantly localized within the mucosal compartment of the infundibulum. Strong cytoplasmic staining was observed in non-ciliated epithelial cells, whereas ciliated cells exhibited minimal to absent immunoreactivity (Fig. 2). In addition, vimentin expression was detected in the endothelial lining of blood vessels within the lamina propria–submucosa and the stratum vasculare, indicating its association with stromal and vascular components.

Desmin immunoreactivity was strongly expressed in both the inner circular and outer longitudinal layers of the tunica muscularis (Fig. 3). Within the stratum vasculare, moderate desmin staining was observed in the tunica media of blood vessels, although the intensity was lower than that in the principal muscular layers.

Notably, extensions of the inner muscular layer projected into the lamina propria–submucosa of the primary mucosal folds, where desmin-positive smooth muscle fibers were clearly evident. In contrast, within secondary mucosal folds, desmin immunoreactivity was confined to the tunica media of blood vessels, with no extension of muscular elements into the fold cores. Tertiary folds lacked desmin

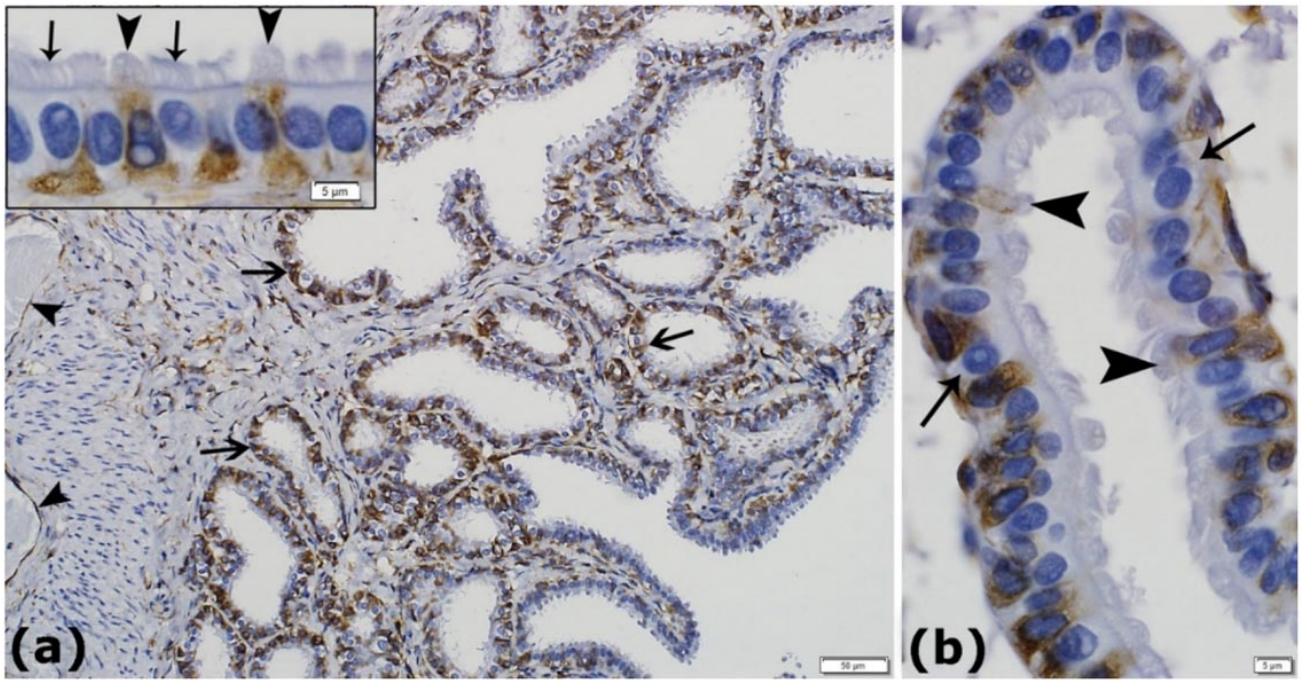


Fig. 2. Immunohistochemical localization of vimentin in the infundibulum of the tube uterine ofdromedary camel. (a) General view showing vimentin immunoreactivity predominantly localized in the epithelial layer (arrows) and in the endothelium of blood vessels (arrowheads) within the lamina propria. Inset: Higher magnification demonstrating strong cytoplasmic immunoreactivity in non-ciliated epithelial cells (arrows), while ciliated cells show little to no staining. (b) Higher magnification of a tertiary mucosal fold lined by simple columnar epithelium, showing vimentin immunoreactivity in the cytoplasm of non-ciliated secretory cells with dome-shaped apical surfaces (arrowheads), whereas ciliated cells remain largely unstained (arrows). Scale bars: (a) 50 µm; inset and (b) 5 µm.

immunoreactivity entirely, consistent with the absence of smooth muscle components in these regions (Fig. 3).

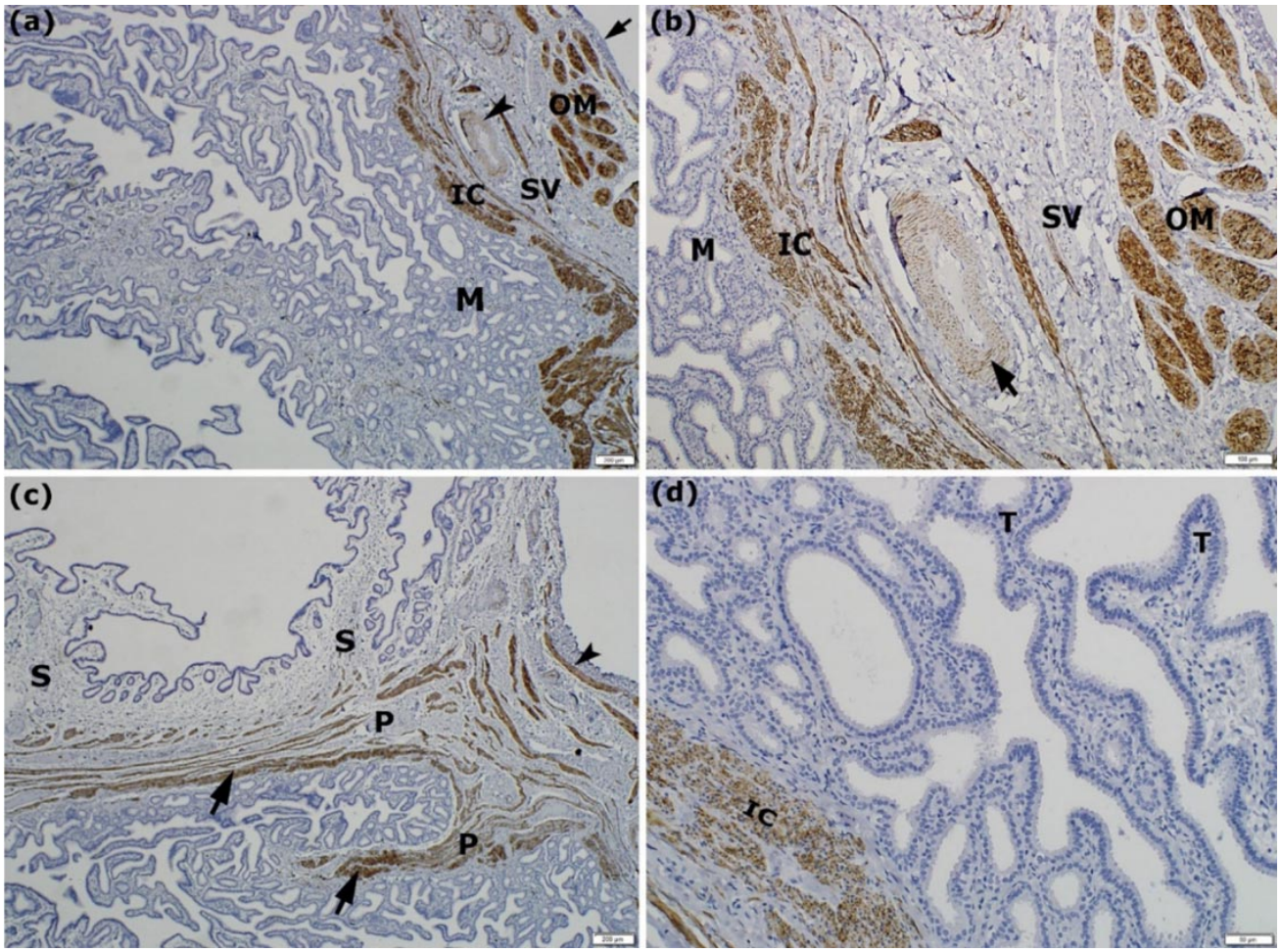


Fig. 3. Immunohistochemical localization of desmin in the infundibulum of the uterine tube of dromedary camel. (a) General view showing strong desmin immunoreactivity in the inner circular (IC) and outer longitudinal (OM) layers of the tunica muscularis. The stratum vasculare (SV) is evident between the muscle layers, containing blood vessels (arrowhead). (b) Higher magnification illustrating moderate desmin immunoreactivity in the tunica media of blood vessels (arrow), which is weaker than that observed in the surrounding smooth muscle layers (IC and OM). The tunica mucosa (M) is also indicated. (c) Extension of desmin-positive smooth muscle fibers (arrows) from the inner muscular layer into the lamina propria of the primary mucosal folds (P). In contrast, secondary folds show minimal to absent immunoreactivity, while arrowheads indicate the outer muscular layer. (d) Absence of desmin immunoreactivity in tertiary mucosal folds (T), with staining confined to the tunica muscularis, including the inner circular layer (IC). Scale bars: (a, c) 200 μm; (b) 100 μm; (d) 50 μm.

Smooth muscle actin (SMA) showed immunoreactivity largely comparable to that of desmin, with strong expression in the tunica muscularis and moderate staining in vascular smooth muscle. However, SMA showed a slightly broader distribution within vascular components than desmin (Fig. 4).

Transmission electron microscopy

Ultrastructural examination of the infundibulum revealed a simple columnar epithelium composed of ciliated and non-ciliated (secretory) cells (Fig. 5a). Both cell types displayed euchromatic nuclei with prominent nucleoli, indicating high transcriptional activity (Fig. 5b). A thin, electron-dense basement membrane separated the epithelium from the underlying lamina propria, which consisted of loosely arranged connective tissue fibers (Fig. 5c). The apical surfaces of both cell types exhibited microvilli (Fig. 5d).

Ciliated cells possessed numerous apical cilia with the characteristic 9+2 microtubular axonemal structure, anchored to electron-dense basal bodies (Figs. 5d and 6a). The subapical cytoplasm contained a high density of

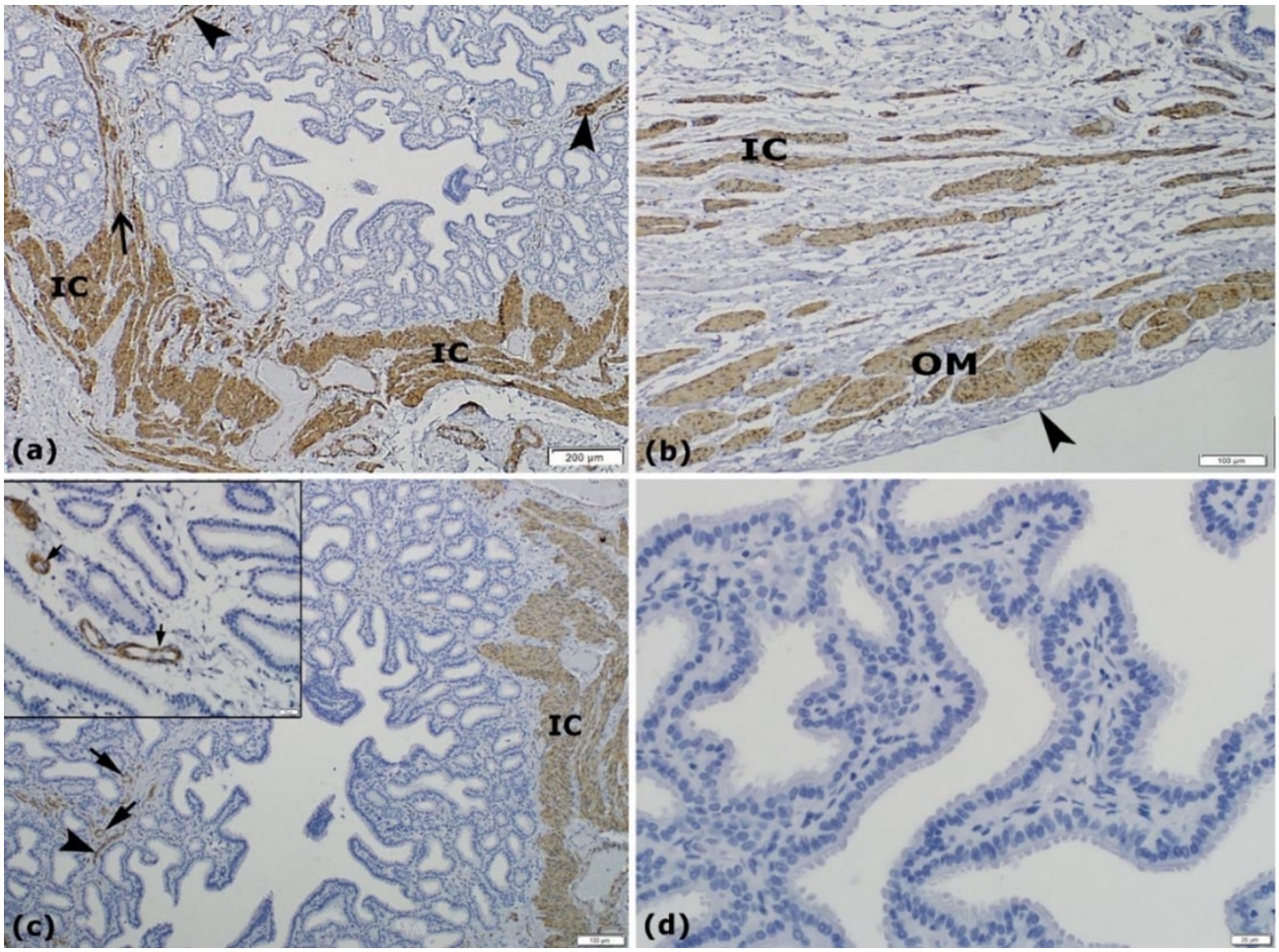


Fig. 4. Immunohistochemical localization of smooth muscle actin (SMA) in the infundibulum of the uterine tube of dromedary camel. (a) General view showing strong SMA immunoreactivity in the inner circular layer of the tunica muscularis (IC), with extension of SMA-positive smooth muscle fibers into the primary mucosal folds (arrow). Secondary folds show weaker immunoreactivity (arrowhead). (b) Higher magnification demonstrating strong SMA immunoreactivity in both the inner circular (IC) and outer longitudinal (OM) layers of the tunica muscularis, as well as in the tunica serosa (arrowhead). (c) SMA immunoreactivity in the inner circular layer (IC). In secondary mucosal folds, staining is confined to the tunica media of blood vessels (arrow). Inset: Higher magnification of the lamina propria showing SMA-positive vascular smooth muscle (arrows). (d) Absence of SMA immunoreactivity in tertiary mucosal folds. Scale bars: (a) 200 µm; (b) 100 µm; (c) 100 µm; inset 50 µm; (d) 50 nm.

mitochondria (Fig. 6b), consistent with the energy demands of sustained ciliary activity. Large cytoplasmic inclusions resembling lysosome-like structures, containing lipid droplets and electron-dense material, were frequently observed in ciliated cells (Fig. 6c).

Non-ciliated cells exhibited apical cytoplasmic protrusions (blebs) associated with microvilli (Fig. 7a). Their cytoplasm contained numerous secretory granules of varying size and electron density, ranging from moderate to intensely electron-dense (Figs. 5a and 6a). A well-developed Golgi complex and abundant rough endoplasmic reticulum were prominent, reflecting high secretory activity (Figs. 7a and 7b).

DISCUSSION

The present study demonstrates that the structural organization of the infundibulum of uterine tube of the camel is broadly comparable to that reported in other mammalian species (Bacha & Bacha, 2011; Marettová & Maretta, 2014; Ahmed, 2023). However, the findings further emphasize that the uterine tube is not merely a passive conduit but a highly dynamic and functionally specialized organ that actively regulates gamete transport, fertilization, and early embryonic development (Bastos *et al*., 2022; Pranomphon *et al*., 2024). In this context, the integration of epithelial specialization and cytoskeletal organization observed in the present study provides important insight into the structural basis of tubal function.

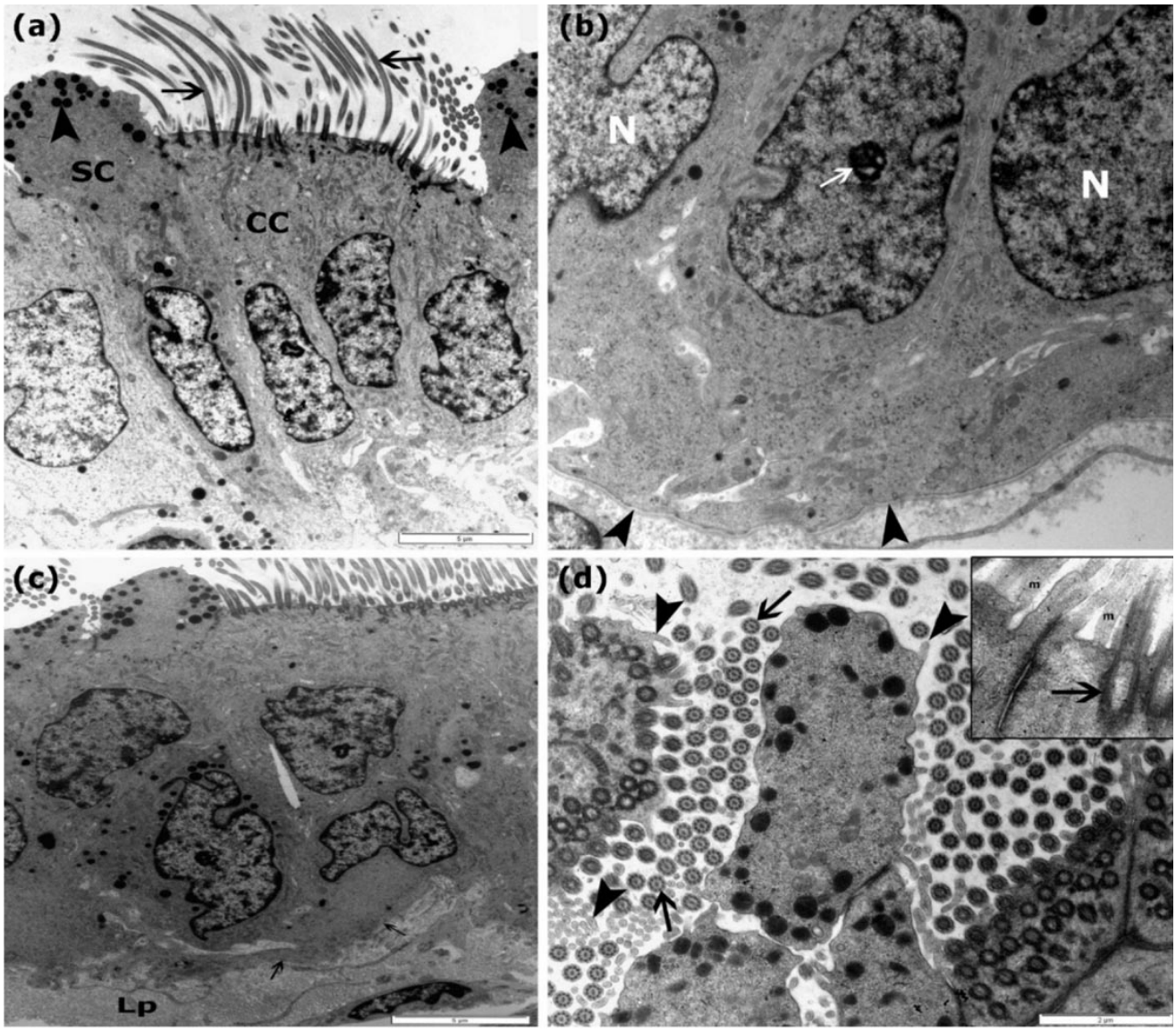


Fig. 5. Transmission electron micrographs of the infundibulum of the uterine tube of dromedary camel. in the infundibulum of the uterine tube of dromedary camel.(a) Apical region of the epithelium showing ciliated cells (CC) with numerous cilia (arrows) and adjacent non-ciliated secretory cells (SC) containing electron-dense secretory granules (arrowheads). (b) Epithelial cells exhibiting euchromatic nuclei (N) with prominent nucleoli (arrow). (c) Thin, continuous basement membrane (arrows) separating the epithelium from the underlying lamina propria (LP). (d) Cross-section of cilia displaying the typical 9+2 axonemal arrangement (arrows). Microvilli are also visible (arrowheads). Inset: Apical region of ciliated cells showing microvilli (m) and basal bodies (arrow). Scale bars: (a–c) 5 nm; (d) 2 nm; inset 1 nm.

Histologically, the infundibulum of uterine tube exhibited a typical trilaminar organization consisting of the mucosa, tunica muscularis, and serosa. In contrast to previous reports describing a distinct submucosa in both prenatal and adult camels (Mohey-Elsaeed *et al*., 2016; Oyelowo *et al*., 2021), the current findings indicate a structural continuity between the mucosa and underlying connective tissue. This observation aligns with reports in other domestic mammals and avian species (Priedkalns & Leiser, 2006; Young *et al*., 2013) and suggests that such continuity may facilitate efficient mechanical integration between epithelial and stromal compartments during tubal motility.

The mucosal epithelium, composed of ciliated and non-ciliated (secretory) cells, reflects the classical organization of the mammalian uterine tube. The extensive mucosal folding observed in the camel infundibulum likely increases luminal surface area, thereby enhancing secretory

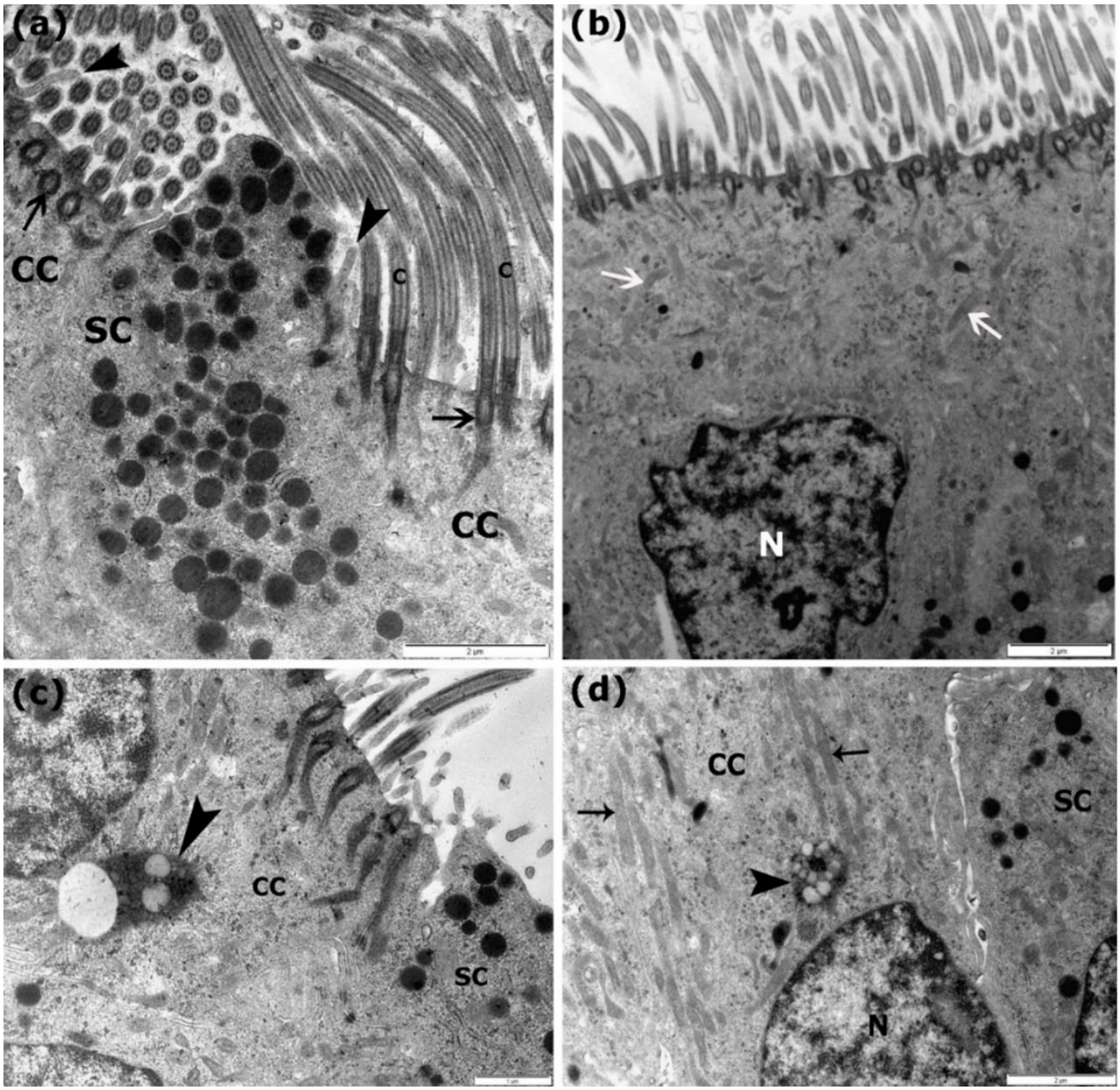


Fig. 6. Transmission electron micrographs of the infundibulum of the uterine tube of dromedary camel. (a) Apical region of the epithelium showing cilia (c) of ciliated cells (CC) anchored to electron-dense basal bodies (arrows). Microvilli (arrowheads) are present on both ciliated and non-ciliated secretory cells (SC). (b) Ciliated cell exhibiting numerous mitochondria (arrows) concentrated in the apical cytoplasm beneath the ciliary border. (c, d) Ciliated cells (CC) contain lysosome-like structures (arrowheads) with lipid droplets and heterogeneous electron-dense material. Abundant elongated mitochondria (arrows) are also evident. Adjacent non-ciliated secretory cells (SC) are visible. Scale bars: (a, b) 2 nm; (c, d) 2 nm.

and absorptive capacities. Functionally, ciliated cells contribute to the directed transport of oocytes and early embryos through coordinated ciliary beating, whereas secretory cells produce tubal fluid enriched with glycoproteins and bioactive molecules essential for fertilization and early embryonic development (Coy *et al*., 2012; Maillo *et al*., 2016; Kırbas Dogan *et al*., 2019; González-Brusi *et al*., 2020). The strong PAS reactivity observed in non-ciliated cells further supports their active role in glycoprotein synthesis, which is known to facilitate sperm capacitation, gamete interaction, and embryo viability (Leese *et al*., 2008; Li & Winuthayanon, 2017). Collectively, these features highlight the infundibulum as a key regulatory interface in early reproductive events.

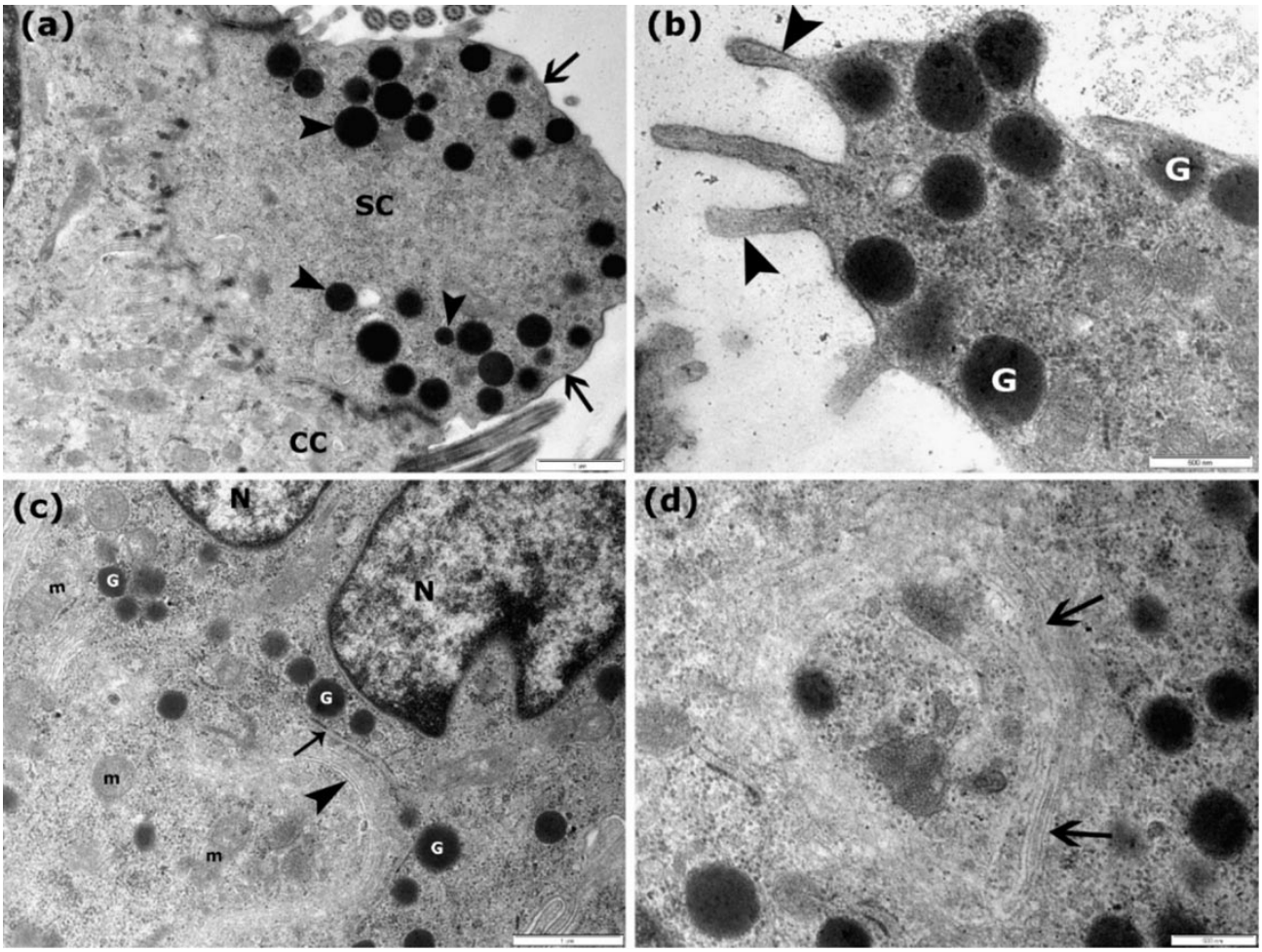


Fig. 7. Transmission electron micrographs of secretory cells in the in the infundibulum of the uterine tube of dromedary camel. (a) Non-ciliated secretory cell (SC) with numerous electron-dense secretory granules (arrowheads) and an apical cytoplasmic bleb (arrow). Adjacent ciliated cells (CC) are present. (b) Higher magnification of a cytoplasmic bleb showing surface microvilli (arrowheads) and accumulated secretory granules (G). (c) Secretory cell cytoplasm containing granules of varying size and density (G), rough endoplasmic reticulum (arrow), Golgi complex (arrowhead), and mitochondria (m). N, nucleus. (d) Prominent Golgi apparatus (arrows). Scale bars: (a) 1 nm; (b) 500 nm; (c) 1 nm; (d) 0.5 nm.

The immunohistochemical findings in the present study provide important insight into the cytoskeletal organization underlying these functions. Vimentin immunoreactivity was predominantly localized in non-ciliated epithelial cells and vascular endothelium, indicating a role in maintaining cellular integrity and mechanical resilience. Although vimentin is classically associated with mesenchymal cells, its expression in epithelial cells has been linked to cytoskeletal remodeling, functional adaptation, and enhanced resistance to mechanical stress (Ivaska *et al*., 2007; Lowery *et al*., 2015). In the present study, its localization within secretory epithelial cells proposes a functional role in accommodating the mechanical demands of apocrine-like secretion. This adaptation may be particularly relevant in camels, where reproductive processes must be maintained under environmental stress, including high temperatures and dehydration (Ridge *et al*., 2022).

Desmin and smooth muscle actin (SMA), well-established markers of smooth muscle differentiation (Skalli *et al*., 1989; Rangdaeng & Truong, 1991), showed strong immunoreactivity in the tunica muscularis, confirming the presence of well-differentiated, functionally active smooth muscle layers. The strong expression of desmin in both the inner circular and outer longitudinal layers underscores its essential role in maintaining structural integrity and coordinated contractile activity (Takamatu *et al*., 2023). Moderate desmin immunoreactivity in the vascular tunica media further supports its involvement in vascular stability, although the reduced intensity likely reflects lower contractile demands than those of the main muscular layers (Hnia *et al*., 2015).

A notable finding of this study is the extension of desmin-positive smooth muscle fibers into the lamina propria

of primary mucosal folds, offering a specialized mechanism for localized contractility. This structural arrangement may enhance the fine regulation of luminal dynamics, thereby facilitating oocyte capture and transport. In contrast, the absence of desmin immunoreactivity in secondary and tertiary folds indicates a functional hierarchy in which contractile elements are confined to primary folds, while higher-order folds primarily serve to increase surface area. The distribution of SMA closely paralleled that of desmin, although with slightly broader localization in vascular components, further supporting its role as a key regulator of smooth muscle contraction and tissue motility (Kim *et al*., 2020; Mahabharathi *et al*., 2024). Together, these findings highlight the coordinated role of cytoskeletal elements in maintaining both structural organization and functional motility within the camel uterine tube.

Ultrastructural observations in this study reinforce the functional specialization of the infundibulum epithelium. The presence of euchromatic nuclei and prominent nucleoli in both epithelial cell types indicates high metabolic and transcriptional activity. In ciliated cells, the abundance of mitochondria in the subapical region reflects the high energy demands associated with sustained ciliary motility, which is essential for effective gamete and fluid transport. The presence of lysosome-like inclusions may be related to intracellular degradation or resorptive processes, as reported in other species (Eriksen *et al*., 1994; Murray, 1997).

In contrast, non-ciliated secretory cells exhibited extensive rough endoplasmic reticulum, a well-developed Golgi complex, and numerous electron-dense secretory granules, consistent with active protein synthesis and secretion. The presence of apical cytoplasmic blebs further supports an apocrine-like mode of secretion, as described in mammalian reproductive epithelia (Lauschová, 2003; Waqas *et al*., 2016; Rojas *et al*., 2017). This mode of secretion may facilitate the release of complex bioactive molecules into the of uterine tube lumen, contributing to the regulation of fertilization and early embryonic development.

The organization of the tunica muscularis, including the presence of a well-developed lamina vascularis between muscle layers, is consistent with reports in domestic mammals and avian species (Priedkalns & Leiser, 2006; El-Desoky & Mustafa, 2019). Importantly, the extension of smooth muscle fibers into primary mucosal folds represents a notable structural specialization. In most domestic species, mucosal folds are primarily supported by connective tissue and lack a distinct muscularis mucosae (Priedkalns & Leiser, 2006; Young *et al*., 2013; Ahmed *et al*., 2023). Therefore, the presence of smooth muscle elements within these folds may provide an additional mechanism for localized contractile activity, complementing the rhythmic contractions of the tunica muscularis and enhancing the efficiency of oocyte transport.

CONCLUSION

This study shows that the infundibulum of uterine tube of the dromedary camel is a special and active part. It is characterized by organized cell structures that facilitate secretion, stability, and controlled movement. This structure likely helps the camel reproduce successfully under harsh conditions. More studies using exact and practical methods are needed to understand how these changes are controlled.

Conflict of interest. The authors declare that they have no competing interests.

EISSA, L.; YASEEN, R. B.; ELSEORY, A. M. A.; AL-THNAIAN, T. A. & ELHASSAN, M. M. O. Especialización histológica y citoesquelética del infundíbulo de la tuba uterina del camello: adaptaciones estructurales para la función reproductiva. *Int. J. Morphol., 44(4)*:1337-1349, 2026.

RESUMEN: El infundíbulo de la tuba uterina proporciona un microambiente altamente especializado, esencial para la captura del ovocito, la fecundación y el desarrollo embrionario temprano. En el camello dromedario (*Camelus dromedarius*), la adaptación de este segmento al estrés ambiental está mediada por modificaciones estructurales y del citoesqueleto coordinadas. Sin embargo, las bases celulares de estas adaptaciones aún no son comprendidas suficientemente. Este estudio investigó la organización histológica, la distribución de proteínas del citoesqueleto y las características ultraestructurales del infundíbulo de la tuba uterina. Se examinaron muestras de tejido de nueve camellas adultas no gestantes mediante histología convencional, histoquímica de ácido peryódico de Schiff (PAS), inmunohistoquímica para vimentina, desmina y actina de músculo liso (SMA), y microscopía electrónica de transmisión. Los resultados histológicos mostraron un extenso plegamiento jerárquico de la mucosa, revestida por un epitelio cilíndrico simple. Este epitelio estaba compuesto por células ciliadas y secretoras. Se identificó una fuerte reactividad al PAS en las células secretoras. Inmunohistoquímicamente, la inmunorreactividad a la vimentina se localizó predominantemente en las células epiteliales no ciliadas y en el endotelio vascular, lo que sugiere un papel en la estabilidad epitelial y la organización del estroma. La desmina y la SMA se expresaron fuertemente en la túnica muscular, con extensiones hacia los ejes de los pliegues mucosos primarios. Ultraestructuralmente, las células secretoras mostraron abundante retículo endoplásmico rugoso, un complejo de Golgi prominente y gránulos electrodensos. Las células ciliadas contenían numerosas mitocondrias, lo cual es consistente con una actividad ciliar sostenida. La formación de protrusiones citoplasmáticas apicales (blebbing) en las células secretoras sugirió un modo de secreción de tipo apocrino. En conclusión, el infundíbulo de la tuba uterina de camello presenta cambios coordinados en sus células de revestimiento y proteínas estructurales, lo que resulta en la integración de funciones de

secreción, resistencia mecánica y áreas contráctiles. Es probable que estas características estructurales sean importantes para una reproducción exitosa en condiciones ambientales desafiantes.

PALABRAS CLAVE: *Camelus dromedarius*; Infundíbulo de la tuba uterina; Remodelación del citoesqueleto; Especialización epitelial; Inmunohistoquímica; Microscopía electrónica de transmisión.

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