

Review

A new morpho-functional classification of the Fallopian tube based on its three-dimensional myoarchitecture

U. Muglia¹ and P.M. Motta²

¹Institute of Veterinary Anatomy 1, University of Messina, Italy and

²Department of Anatomy, University of Rome "La Sapienza", Rome, Italy

Summary. The recent direct observations, under scanning electron microscopy (SEM), of the three-dimensional architecture of myosalpinx in different mammals allows us classify salpinxes according to the myoarchitecture of their tubo-uterine junction (TUI) and isthmus segments.

Based upon the myoarchitecture of the outer wall of the TUI we could find barrier-like species (rat and sow), sphincter-like species type a (rabbit and ewe) and sphincter-like species type b (cow and woman). The different architecture of TUI can be explained by the different nature of the mating process. Based upon the myoarchitecture of the isthmus we could distinguish type 1 (rat) and type 2 (rabbit, ewe, sow, cow and woman) salpinxes. In the latter the close fusion of musculature deriving from the meso (extrinsic musculature) with the musculature of salpinx (intrinsic musculature) suggests the existence of a unique mesosalpinx contractile system.

The myosalpinx is mostly made up of a single network of muscular fibers. Such a plexiform structure, owing to the uneven distribution of fibers, rather than producing a series of regular contraction waves, is more likely to generate random contraction waves. The random propagation of muscular network contraction may deform the plexiform wall of the myosalpinx causing the stirring of tubal contents. By such a stirring movement the contact between hormones and nutrients and the eggs or embryos is intensified, thus favoring a correct fertilization and early embryo development. Taken all together, these systematic results probably suggest an additional and rather new function for the musculature of the tube, namely to increase fertility in a large number of species.

Key words: Fallopian tubes, Microanatomy, Smooth muscle cells, Scanning electron microscopy

Offprint requests to: Prof. Ugo Muglia, Institute of Veterinary Anatomy, Via S. Cecilia, 30, I-98123 Messina, Italy. Fax: +39 90 2934009. e-mail: mugliau@imeuniv.unime.it

Introduction

The first description of the oviductal musculature (myosalpinx) in the woman dates back to Williams (1891), even though the earliest data on its architecture came from successive observations carried out on histological sections by Andersen (1927, 1928) on the sow. For nearly a century, from the early results up until 1970, numerous data on the myosalpinx architecture of a large number of species were reported. These were recorded only on the basis of bidimensional observations of sections under the light microscope (LM) and transmission electron microscopy (TEM). Such results were mainly based on the concept that the myosalpinx architecture is organized in stratified muscular layers as occurs in the intestine muscular wall. Such layers were described as variable in number and were constituted by muscular fibers (grouped or not in bundles) having different orientation. The direct observations, under scanning electron microscopy (SEM), of the three-dimensional architecture of the myosalpinx, made possible by a technique involving extraction of interstitial connective tissue and microdissection by ultrasounds (Takahashi-Iwanaga and Fujita, 1986; Low, 1989; Muglia et al., 1991a), revealed that the myosalpinx architecture in different mammalian species, independently from the various stages of estrous cycle (Muglia et al., 1991b), is commonly made up of a single network of muscular fibers (Muglia et al., 1992).

The knowledge of the architecture of the myosalpinx is essential to understand its function. Therefore, it is important to define a structural model as a fixed parameter for reference. In fact, for example, if the reference model of the myosalpinx architecture is that of the gut, the orthogonal disposition of its smooth muscle fibers is related to generate and to co-ordinate peristaltic movements in an antagonistic manner. On the contrary, if the reference model is that of other hollow organs such as the epididymis (Uehara et al., 1990), the ureter (Tachibana et al., 1985), the urinary bladder (Uehara et al., 1990) or the gall bladder (MacPherson et al., 1986)

where the arrangement of smooth muscles is plexiform, the resulting contraction does not allow us to hypothesize a function of regular peristaltic movement (Gosling, 1979). Furthermore, the most recent studies on the myosalpinx architecture emphasize the need to clarify if and to what extent the musculature deriving from the mesosalpinx, defined as *extrinsic* (salpinx) musculature by a number of Authors, is integrated in the salpinx musculature (*intrinsic* musculature). The numerous and often contradictory opinions on this matter found in the literature are discussed hereafter. These different descriptions, mostly taken from indirect observations by light and transmission microscopy and directly by scanning electron microscopy, are reported with the aim to provide a synthesis among various conflicting data.

Literature data on the myosalpinx architecture

Woman

Isthmus¹

According to the wide literature on the subject in woman, the *indirect* observations of sections under light and transmission electron microscopy, showed that the isthmus architecture is constituted by two or three variously oriented muscular fiber layers.

In particular, according to Nilsson and Reinius (1969) and Pauerstein et al. (1970), the musculature of the isthmus is organized into three layers: an outer longitudinal or spiral *extrinsic* one (Verdugo, 1986), an intermediate circular or plexiform one (Ferraris, 1947) and an innermost longitudinal layer. In other reports, the existence of an inner longitudinal (David and Czernobilsky, 1968; Fawcett, 1986), or outer longitudinal layer (Beck and Boots, 1974) was not mentioned.

Early studies (Fumagalli, 1949; Kipfer, 1950) by the use of a three-dimensional (3-D) reconstruction based upon LM observations, as reviewed by Horstmann and Stegner (1966), suggested that the musculature of the intermediate layer consisted of two systems of intermingled spiral fibers arranged in a clockwise or anticlockwise manner. These authors described a fusion between the musculature deriving from the mesosalpinx (*extrinsic* musculature) and *intrinsic* musculature.

The *direct* observations (Fig. 1) by means of SEM were limited to samples in which the mesosalpinx musculature component (*extrinsic* musculature) was lacking. The intrinsic musculature was composed of irregularly running bundles of smooth muscle cells (SMC), changing their orientation within the myosalpinx and displaying longitudinal, oblique and circular directions. The muscular bundles anastomosed and intermingled with other bundles running at different

levels in the tube wall actually giving rise to a wide and complex muscular network in which no distinct layers were recognized (Vizza et al., 1991).

Ampulla

In the majority of studies based on the *indirect* observations a clear cut layering of SMC bundles was reported as follows: an outer longitudinal layer; an inner circular layer; and a discontinuous innermost longitudinal layer (David and Czernobilsky, 1968; Nilsson and Reinius, 1969; Woodruff and Pauerstein, 1969; Pauerstein et al., 1970, 1974; Beck and Boots, 1974; Pauerstein and Eddy, 1979; Verdugo, 1986; Hunter, 1988; Brosens and Gordon, 1990; Fujii et al., 1990; Fawcett, 1986). In other studies it was noted that the SMC bundles of the inner layer were not precisely circularly arranged. Therefore, it was suggested that two fiber systems were present: clockwise and counter-clockwise spiral fibers intermingled to form a plexiform structure (Ferraris, 1947; Fumagalli, 1949; Kipfer, 1950; Stange, 1952a,b; Horstmann and Stegner, 1966). In particular, Stange (1952a,b) postulated that, because of its plexiform arrangement, the myosalpinx of the pre-ampulla and the fimbria could act at the same time as a sphincter and a peristaltic pump involved in ovum capture. Daniel et al. (1975a), even having reported longitudinal and circular SMC bundles, denied the existence of two clear-cut concentric layers in the ampulla of the woman.

The direct observations (Fig. 1) (Vizza et al., 1995), showed a muscular wall made up of a continuous network of randomly anastomosed SMC bundles with a multidirectional arrangement.

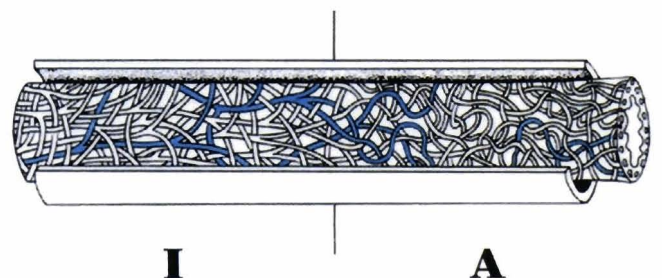
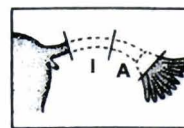


Fig. 1. The diagram summarizes the 3-D architecture of the myosalpinx in the woman as revealed by SEM after maceration. Blue: some details of *intrinsic* musculature; I: Isthmus; A: Ampulla.

¹: in woman the extramural portion of tubo-uterine junction is generally considered as a part of isthmic segment

Cow

Tubo-uterine junction (TUV) Isthmus and Ampulla

In the cow the *indirect* observations showed, according to Bignardi (1948), muscle fibers forming outer circular and inner discontinuous longitudinal or spiral layers in the extramural portion of the TUV. These layers, which were not distinctly separated, gradually decreased in the isthmus and were completely lacking at the end of the ampulla. Schilling (1962) suggested that the myosalpinx of Ungulates may be constituted by spiral fibers running deeper from the surface towards the

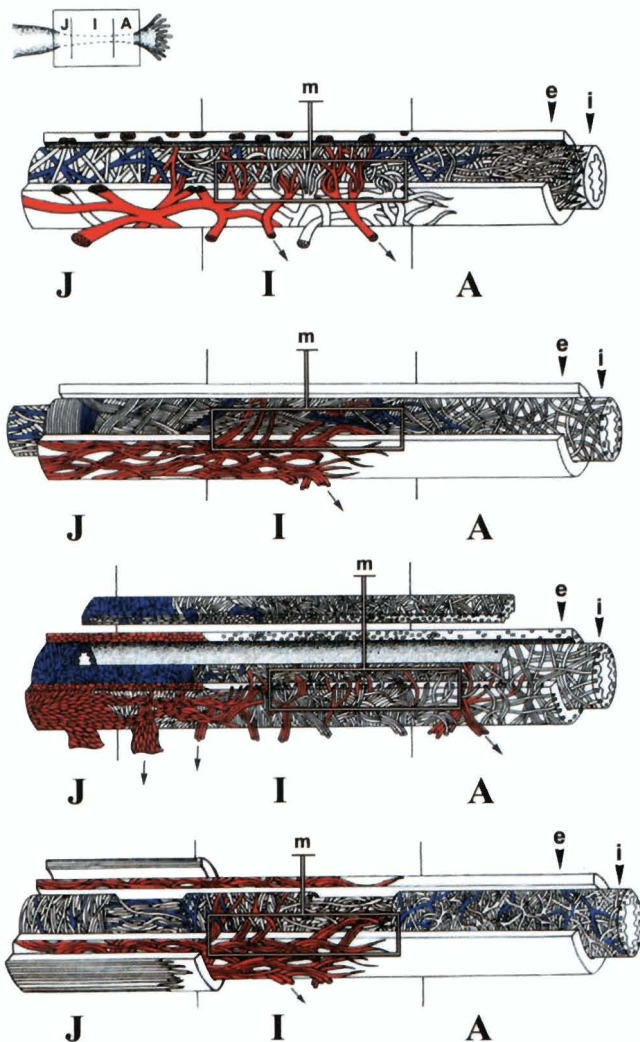


Fig. 2. The diagrams summarize the 3-D architecture of the myosalpinx as revealed by SEM after maceration. From the top to the bottom: cow, ewe, sow, rabbit. Red: some details of *extrinsic* musculature; blue: some details of *intrinsic* musculature. J: extramural segment of the TUV; I: Isthmus; A: Ampulla; e: *extrinsic* musculature; i: *intrinsic* musculature; m: merging points between *extrinsic* and *intrinsic* musculature; arrows: mesosalpinx.

base of mucous folds. The variable pitch of such spirals would account for the differences in the architecture of the myosalpinx between the tubal segments. Weeth and Herman (1952) described an outermost circular and an innermost longitudinal layer in TUV, isthmus and ampulla. Wrobel et al. (1993) reported in the extramural portion of the TUV an incomplete outer system of mostly longitudinal isolated bundles intermingled with subserosal muscle bundles (*extrinsic* musculature?) having a variable direction and a thick intermediate circular or spiral layer and an inner longitudinal layer.

The *direct* observations (Fig. 2) showed *extrinsic* muscle fibers in the TUV (Muglia et al., 1997a) joined in distinct, thick bundles which followed a roughly longitudinal or oblique course. These bundles originated from the mesosalpinx, reached and ran along the surface of the underlying *intrinsic* musculature, where they unravelled in many points. The bundles often bifurcated and anastomosed along their course forming a network. In the isthmus the architecture appeared constituted by elongated, quite regularly outlined muscle fibers joining in thick, isolated, oblique bundles which were more numerous than in the TUV and leaned against the periphery of the *intrinsic* musculature. Before merging into the latter, the bundles often bifurcated and anastomosed, thus forming a network structure in some areas of *intrinsic* myosalpinx. In the ampulla the fibers were rare and isolated. In the *intrinsic* musculature of extramural portion of the TUV, in the isthmus and in the ampulla the myosalpinx showed oblique bundles of variable orientation and length, which were loosely distributed in the TUV and densely packed in both isthmus and ampulla. These bundles intersected and merged into the surrounding musculature forming a complex network.

Ewe

Tubo-uterine junction (TUV), Isthmus and Ampulla

Studies performed by *indirect* observations of the architecture of myosalpinx revealed muscle fibers originating from the mesosalpinx (*extrinsic* musculature) along with fibers proper to the tube (*intrinsic* musculature) (Bignardi, 1948). The former were arranged in isolated, longitudinal bundles immersed in the dense subperitoneal connective tissue. The latter formed an outer circular and inner longitudinal layer in the extra-mural portion of the TUV and in the isthmus, whereas they had a longitudinal course in the ampulla. Schilling (1962) suggested that the myosalpinx of Ungulates was probably constituted by spiral fibers running deeper from the surface towards the base of mucous folds. The variable pitch of such muscular spirals would account for the differences in the architecture of the myosalpinx between the tubal segments observed in transverse section under the light microscopy. Beck and Boots (1974) described two distinct thin, longitudinal muscle layers, an outermost

and an innermost one, enveloping an intermediate thick, circular layer in the isthmus and ampulla of the goat myosalpinx.

The direct observations of the myosalpinx showed an *extrinsic* and *intrinsic* musculature (Fig. 2) (Muglia et al., 1996b). In the *extrinsic* musculature, the TUJ fibers joined in flattened bundles which followed an almost longitudinal course. Furthermore, in this area they intersected at multiple plane levels remaining independent from the underlying *intrinsic* musculature. On the contrary, in the isthmus, in which this component appeared reduced in thickness if compared to that present in the TUJ, the sparse oblique bundles, seen at the periphery of the *intrinsic* musculature, leaned against it and frequently merged into it. The *intrinsic* musculature showed the characteristic architecture of each tubal segment. In the TUJ it was made up of densely packed, elongated fibers, which thinned out at their extremities. In this segment, the muscle fibers were arranged in concentric, tightly assembled monolayered shells which formed a compact coat. Below these fibers, loosely distributed, ribbon-like fibers could be seen following a rather longitudinal course and intersecting at multiple planes. Such fibers decreased in number as they gradually reached the base of mucous folds. In the isthmus the muscular coat, found in the TUJ, gave origin to wide, flattened, oblique bundles of fibers intersecting (one another) and running across multiple planes. In proximity of the ampulla (ampullary-isthmic transitional zone), such bundles followed multiple spatial directions and, as they reached deep areas far from the surface, they showed unravelled extremities merging into the surrounding musculature. In the ampulla the elongated fibers joined, in small numbers, into short, variably oriented bundles which delimited broad spaces. The extremities of these bundles merged into the surrounding musculature, after changing both direction and course plane, thus giving rise to a plexiform structure.

Sow

Tubo-uterine junction (TUJ) Isthmus and Ampulla

In the sow the *indirect* observations of the myosalpinx revealed an outer longitudinal muscular and an inner circular layer, more or less developed in the isthmus and ampulla (Andersen, 1927, 1928; Beck and Boots, 1974). In other studies (Bignardi, 1948), two longitudinal layers originating from the mesosalpinx (*extrinsic* musculature) were found in all tubal segments (TUJ, isthmus and ampulla): an innermost and an outermost layer, enveloping an intermediate circular layer formed by muscle fibers peculiar to the tube (*intrinsic* musculature). Schilling (1962) suggested that the myosalpinx of Ungulates, and particularly of the sow, might be constituted by spiral fibers running deeper from the surface of the organ towards the base of mucous folds. The variable width of such spirals would account for the differences in the architecture of the

myosalpinx between the tubal segments.

Our *direct* observations (Muglia et al., 1997b) revealed a gradual transformation from the *extrinsic* to the *intrinsic* musculature in the TUJ (Fig.2). This depended on the change in cell shape which was regular, spindle-shaped in *extrinsic* and irregular in the *extrinsic* musculature. *Extrinsic* and *intrinsic* musculature formed a unique dense muscular coat. In the *extrinsic* musculature of isthmus and ampulla the SMC became elongated and joined in short bundles, loosely distributed, merging into the deep *intrinsic* musculature, after changing both direction and course plane, participating to the *intrinsic* muscular architecture. Thus, the structure of both *extrinsic* and *intrinsic* musculature of isthmus and ampulla was characteristically plexiform.

Rabbit

Indirect observations

Tubo-uterine junction (TUJ), Isthmus and Ampulla. According to Pauerstein et al. (1970) the myosalpinx consisted of three muscular layers: an outer longitudinal, an intermediate circular and an inner longitudinal one. All these were present throughout the entire length of the salpinx. David and Czernobilsky (1968) reported only two layers in the isthmus: an outer longitudinal and an inner circular one. On the contrary, in other studies (Nilsson and Reinius, 1969), the outer layer was reported to be circular and the inner one longitudinal. Moreover, in these studies a solely circular arrangement of muscle fibers in the ampulla was described, whereas Kushiya (1968) reported two distinct layers in this segment: an outer longitudinal and an inner circular one.

Direct observations (Fig. 2)

TUJ. The extramural portion of the myosalpinx showed outer longitudinal muscular bundles arising from the outer longitudinal layer of the uterus (Muglia et al., 1991b). Such bundles ran parallel to each other as well as to the major axis of the salpinx. In such a way, they formed a well-defined continuous muscular layer extending towards the ampulla and enveloping the proximal portion of the isthmus. A vascular coat - running for the same length and whose vessels anastomosed to form an uneven network beneath the longitudinal layer - was present.

The myosalpinx underlying the vascular network was made up by muscular bundles running deeper from the surface towards the base of the mucous folds. At the most superficial level these bundles followed an uneven circular arrangement and often bifurcated. At a deeper level the same bundles appeared even more irregular, anastomosing repeatedly into several branches that showed different directions thus generating a plexiform arrangement. Some bundles reached the base of the mucous folds and formed wide curves often having opposite concavities, following a rather longitudinal

discontinuous pattern.

Isthmus. The isthmic myosalpinx revealed throughout its length some superficial longitudinal muscular strips, arising from the mesosalpinx (*extrinsic* musculature). These enveloped the underlying *intrinsic* muscular tissue, leaned against and frequently merged into it. The *intrinsic* musculature showed the same structure as at the TUJ, except for the outer longitudinal layer originating from the uterus and the underlying vascular plexus. Both layers were lacking in the isthmus but were present in the TUJ.

Ampulla. A plexiform pattern was noted in this tract except for some isolated superficial strips of *extrinsic* musculature that ran longitudinally as they did in the Isthmus.

Rat

Tube-uterine Junction (TUJ), Isthmus and Ampulla

According to Nilsson and Reinius (1969), by means of the *indirect* observations, the SMC of myosalpinx in the rat were arranged into a coat consisting mostly of circularly arranged fibers in both TUJ and isthmus. In the former, an outer longitudinal layer arising directly from the uterus occurred; at the ampullar and preampullar level it was constituted by one to three longitudinal layers. On the other hand, Beck and Boots (1974) reported two thin longitudinal layers enveloping a third intermediate circular layer at both the isthmic and ampullar level, with the outer longitudinal layer lacking in the infundibulum.

The direct observations (Fig.3) allowed us (Muglia et al., 1996a) to distinguish, within the myosalpinx of the rat, two muscular components independent from each other. One was located within the subperitoneal connective tissue of mesosalpinx (*extrinsic* musculature) and the other one was peculiar to the salpinx (*intrinsic* musculature). The fibers of the *extrinsic* musculature, at the TUJ, were oriented obliquely with respect to the major axis of the salpinx and formed an incomplete, wide spiral layer that enveloped the salpinx. On the other hand, in the isthmus and ampulla these fibers ran tortuously, generating characteristic whorl-like structures. In the *intrinsic* musculature, SMC were packed together and arranged into concentric, monolayered shells tightly assembled to form a coat. At the most superficial level the fibers followed a circular course, whereas at the deepest levels they appeared arranged into a plexiform structure. Furthermore, only in the isthmus, on the surface of the intrinsic musculature, ring-like systems of SMC fibers surrounding the elbow-shaped folds of tubal loops were observed².

Discussion

It is our opinion that the contradictory results and

interpretations found in the literature on the myosalpinx architecture of most mammals mostly depends upon the fact that they were obtained from observations of histological sections. These data, only based on bidimensional parameters, do not provide a correct and exhaustive 3-D description. In fact, in these studies the muscle fiber bundles appear obliquely, longitudinally or unevenly circularly arranged in relation to the percentage of fibers, with different spatial orientation, present in the planes of section. These, in turn, are only very rarely perfectly transverse, especially in a tortuous salpinx such as that of some species (e.g. rat). Moreover, the 3-D reconstruction based on serial sections also reveals serious limitations due to the difficulty of following the course of each fiber bundle. On the basis of these considerations, we believe that the data directly obtained by using the SEM are not conflicting with, and do not invalidate those early reported in the literature. On the contrary, by completing and integrating these ones, they

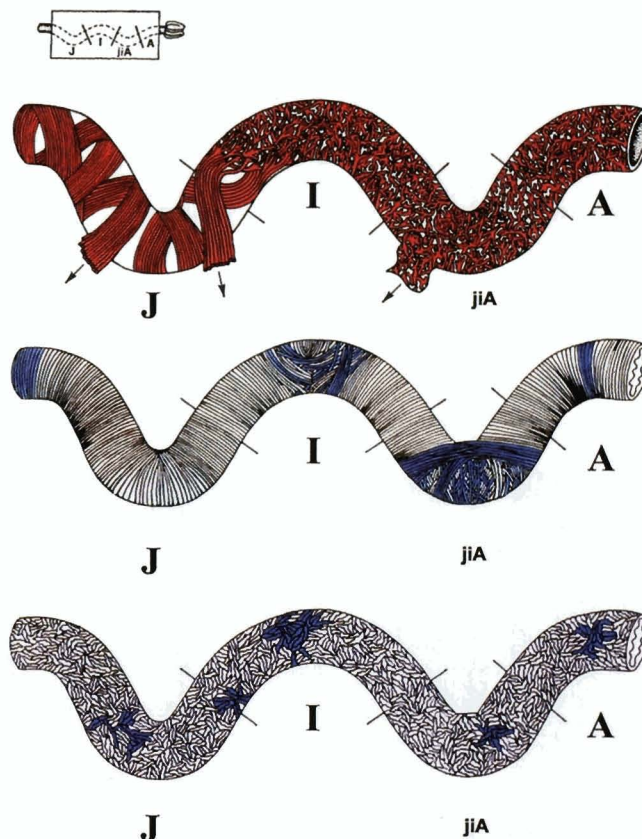


Fig. 3. The diagrams summarize the 3-D architecture of the myosalpinx in the rat as revealed by SEM after maceration. From the top to the bottom: outer level, middle level and inner level. Red: *extrinsic* musculature, blue: some details of *intrinsic* musculature. J: extramural segment of the TUJ; I: Isthmus; jia: Isthmic-ampullary junction; A: Ampulla; arrows: mesosalpinx.

²: the salpinx in the rat is a coiled organ (Nilsson and Reinius, 1969).

provide a clearer micro-topographical 3-D view of the mammalian myosalpinx architecture.

The availability of myosalpinx three-dimensional models as revealed by these more recent studies, which provide greater details with respect to the early observations of the past, offers the opportunity: 1) to classify the real 3-D morphological characteristics of these structures; 2) to more readily interpret these 3-D data from a functional point of view. Thereby, the studies offer an important starting point to discuss more properly some data on the physiology of tubal transport.

Classification of the mammalian salpinx based on the 3-D myoarchitecture and related functional significance

Tubo-uterine junction (Table 1)

On the basis of the features of the myoarchitecture of the outer wall of the TUJ we can distinguish: a)

barrier-like species [e.g. rat (Fig. 4A) and sow] characterized by a robust musculature rich in densely packed SMC fibers; and b) *sphincter-like species*. Among the latter, there are species [such as the rabbit and ewe (Fig. 4B)] characterized by a geometrically organized myoarchitecture. In these animals the *intrinsic* and *extrinsic* musculature are independent (*sphincter-like type a*). Other species such as cow (Fig. 4C) and woman, characteristically show a plexiform tubal myoarchitecture in which the *intrinsic* and the *extrinsic* musculature are closely interwoven (*sphincter-like type b*). As in other segments of the salpinx, the more or less close relation of *intrinsic* and *extrinsic* musculature, found in the species belonging to types a and b, produces a different degree of differentiation from the intrinsic musculature. In particular, the specialization of the intrinsic musculature is inversely related to its integration with the *extrinsic* musculature and vice versa.

The TUJ has the function of preventing and actively controlling, particularly in species with intrauterine

Table 1. Characteristics of TUJ and Isthmus according to myoarchitecture classification.

	PECULIAR FEATURES	SPECIES	RELATION <i>EXTRINSIC</i> / <i>INTRINSIC</i> MUSCULATURE
TUJ			
Barrier-like	Packed structure	Rat Sow	Independent Merged
Sphincter-like type a	Geometrically organized	Rabbit/Ewe	Independent
Sphincter-like type b	Plexiform	Woman/cow	Interwoven
Isthmus			
Type 1	Organized in muscular structures	Rat	Independent
Type 2	Plexiform	Woman Rabbit/Ewe Sow/Cow	Interwoven

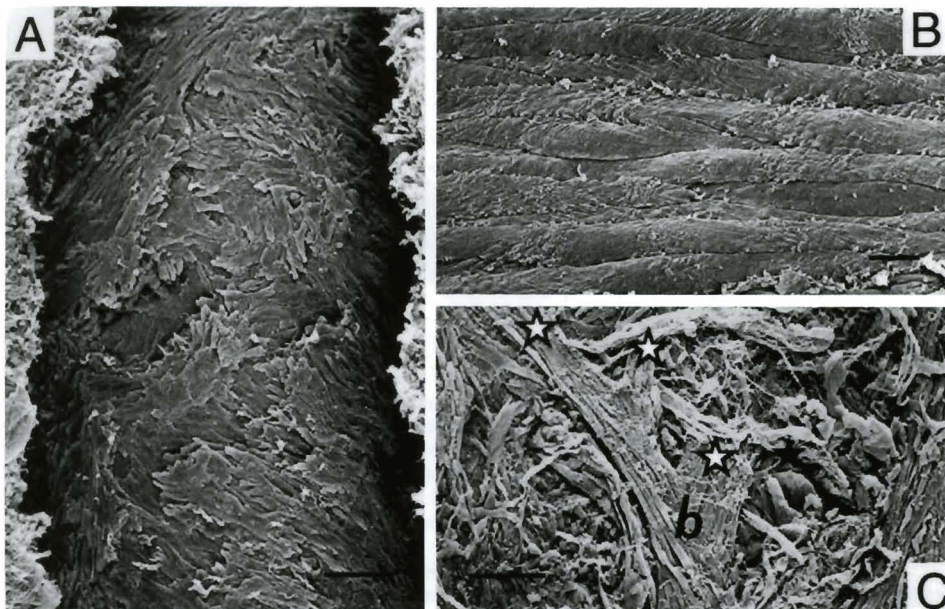


Fig. 4. SEM of the tubo-uterine junction after maceration technique. **A.** Barrier-like salpinx (rat) with densely packed SMC fibers of intrinsic musculature. Bar: 25 μ m. **B.** Sphincter-like type a salpinx (ewe) showing parallel fibers of the circular coat. Bar: 5 μ m. **C.** Sphincter-like type b salpinx (cow). Bundles of the *extrinsic* musculature (b) merging (asterisks) into the underlying *intrinsic* musculature. Bar: 25 μ m.

A new classification of Fallopian tube based on its myoarchitecture

ejaculation, the extrusion of semen plasma and sperm number in the tube (Mann et al., 1956; Hunter and Hal, 1974; Polge, 1978; Einarsson et al., 1980), independently from the whole volume of plasma (Blandau, 1973). To better understand the myosalpinx architecture it is necessary to consider that the role played by the TUJ is notably influenced by different factors, which vary greatly among mammals. In particular, considering the passive transport of spermatozoa, important factors are: 1) the volume of ejaculate together with its physical and biochemical characteristics; 2) the site of semen deposition within the reproductive tract; 3) the anatomy and physiology of the cervix; and 4) the pattern of mating and the number of

spermatozoa (Blandau, 1973).

In barrier-like species (sow, rat) semen deposition occurs in the uterine cavity. In the sow, the glans engages with the uterine cervix during mating (Rigby, 1967). As a result, the semen directly causes a stretching of uterine horns (Hunter, 1973). In the rat, although the penis does not reach the cervix, the semen (produced by a series of rapid and multiple copulations) stretches the uterine horns at the end of mating, similarly to that which occurs in the sow (Hartman and Ball, 1930; Blandau, 1945; Hunter, 1973). Consequently, in these two species (mostly in the sow), a thick muscular wall at the TUJ is required to resist the pressure of semen and to regulate the access of seminal plasma into the tube. This accounts

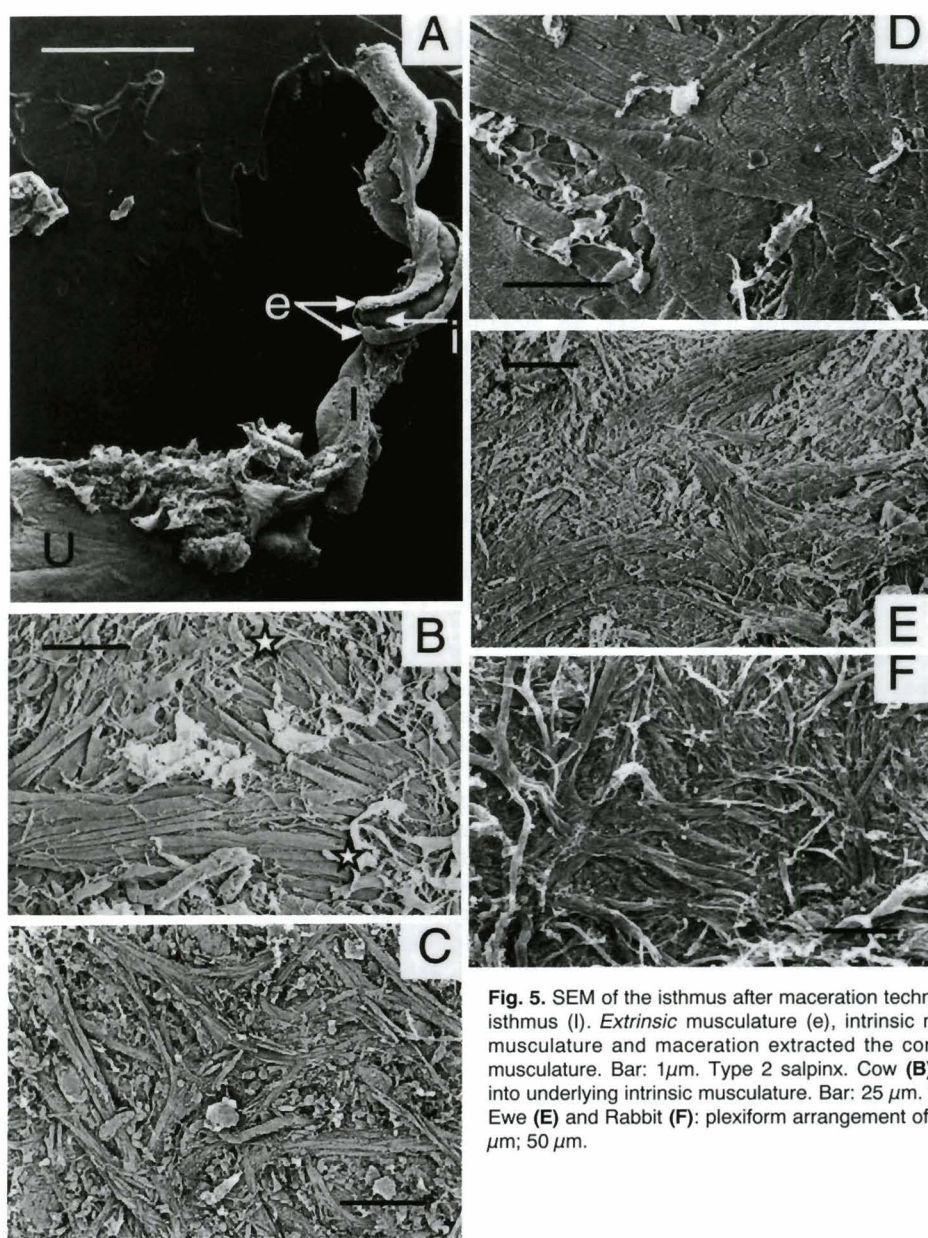


Fig. 5. SEM of the isthmus after maceration technique. Type 1 salpinx. Rat **(A)**: Uterine horn (U), isthmus (I). *Extrinsic* musculature (e), *intrinsic* musculature (i). Sonication broke the *extrinsic* musculature and maceration extracted the connective tissue joining *extrinsic* and *intrinsic* musculature. Bar: 1 μ m. Type 2 salpinx. Cow **(B)**: Merging point (star) of *extrinsic* musculature into underlying *intrinsic* musculature. Bar: 25 μ m. Woman **(C)** (Courtesy of Dr. E.Vizza), Sow **(D)**, Ewe **(E)** and Rabbit **(F)**: plexiform arrangement of *intrinsic* musculature. Bars: 100 μ m; 25 μ m; 50 μ m; 50 μ m.

for the thick sleeve of tightly packed muscular fibers, both in *intrinsic* and *extrinsic* musculature, constituting the TUJ wall. Where, as in the sow, the TUJ is more directly subjected to semen pressure during mating it also accounts for the fact that the *extrinsic* musculature fuses with the *intrinsic* one, resulting in a robust muscular coat. This suggests that the *extrinsic* musculature, by changing its morphology according to the specific tubal segment, may affect the activity of tubal *intrinsic* musculature.

On the other hand, in the rabbit, ruminants and woman, i.e. species that have an intravaginal deposition, uterus and uterine horns are not directly subjected to the pressure of semen. Therefore, a first selection of sperm is performed by the uterine cervix (Mann et al., 1956; Hunter, 1974; Polge, 1978). Thus, the TUJ, rather than functioning as a barrier against the flow of seminal plasma, may have a more active role in modulating the seminal flow, as is witnessed by its complex muscular architecture.

The different TUJ myoarchitecture, found between type a and type b species, may be related to the architecture of myometrium. For example, in the woman (type b) the structure is plexiform in the myometrium as it is in the myosalpinx (Vizza et al., 1997). The structural identity of myometrium and myosalpinx - which allows the consideration of the uterus and TUJ (including the outer-wall portion) as a unique morpho-functional entity - can be explained by the synergy of uterus and TUJ to transport sperm from the uterus to the isthmus through to the TUJ (Edgard and Asdell, 1960; Blandau, 1973). Therefore, it can be concluded that the different architecture of the myosalpinx found in various species at TUJ is closely related to the different nature of the mating process.

Isthmus and ampulla (Table 1)

On the basis of recent 3-D results on the myoarchitecture, as well as external morphological characteristics of the isthmic-ampullary segment, obtained both *in situ* and after removal from the pelvic cavity, the salpinx may be classified in two groups: type 1 and type 2.

Type 1 salpinx. This is peculiar to the rat, whose *extrinsic* musculature is independent of the underlying *intrinsic* musculature (Fig. 5A). The salpinxes have a tortuous course. The myoarchitecture is organized in two layers. The superficial one is composed of the *extrinsic* musculature and the inner deeper one by the *intrinsic* musculature. The most superficial area of the *intrinsic* musculature is organized in distinct muscular structures [i.e. ring-like systems of SMC fibers surrounding the elbow-shaped folds of tubal loops (see Muglia et al., 1996a for further details)]. Data on the topography of the adrenergic innervation of the mesosalpinx in the rat (Brundin et al., 1969) prove that the *extrinsic* musculature possesses a notably higher concentration of adrenergic fibers compared to the *intrinsic* musculature.

These observations support the hypothesis of a micro-structural independence of the two muscular structures in type 1 salpinxes (rat).

Type 2 Salpinxes. The salpinx course is regular. The rather tortuous course of the salpinx described *in vivo* in a number of these species (Nilsson and Reinus, 1969) very likely depends on the relationship that these salpinxes have *in situ* with the meso to which they are attached. This type, in which the *extrinsic* and the *intrinsic* components are closely intermingled (Fig. 5B) is found in a rodent (rabbit), a number of Ungulates (ewe, sow, cow) and in the woman. The myosalpinx architecture is plexiform (Fig. 5C-F).

In most studies the isthmus is considered not only the area of sperm reservoir but also the segment which releases sperm at the time of ovulation in order to fertilize the egg (Hunter, 1986, 1987a; Hunter et al., 1987). For this reason the isthmus performs a primary role in the transport of gametes by means of: a) both a direct and indirect (through flow of tubal fluids) action of ciliary beating; and b) size variation of tubal lumen controlled by the contraction of myosalpinx as well as the edema of mucosa. The constriction of the tubal lumen serves to control the transport of sperm towards the ovary. In fact, in the pre-ovulatory phase it hinders the descent of the egg cell (which is greater in diameter than the spermatozoa), thus causing it to remain at the ampullary-isthmic junction in order to facilitate the encounter of the egg with the spermatozoa (Hunter, 1988). On the contrary, the width of the isthmus lumen is related to an increase of its caliber which, in turn, leads to an increase of the transport and the movement of the early embryo from the ovary to the uterus (Hunter, 1988). The sojourn of the egg in the isthmic-ampullary junction serves to increase its exposure to the still far resident spermatozoa in the TUJ (Hunter, 1977, 1987a). This also avoids its exposition to a relatively high concentration of vital spermatozoa in the intra-mural portion of the TUJ (Hunter, 1987b). The size variation in the tubal lumen, caused by the gradual contraction or relaxation of the myosalpinx, as well as the turgidity of the mucosa, is affected by the balance of ovarian steroids (Hunter, 1977), which in turn potentiate α and β adrenergic receptors of the musculature (Brundin, 1965) through a counter-flow mechanism from the ovarian vein towards the ovarian arteries and uterine tube (Hunter et al., 1983). These activities occur in such a way that the tube musculature can be regarded as a sort of a "physiological sphincter" which probably originates the tube locking mechanism. In type 2 salpinxes the close fusion of the *extrinsic* with the *intrinsic* musculature in the isthmus and, to some extent, in the ampulla is witness to the existence of a unique mesosalpinx contractile system. Considering that in type 1 salpinxes the *extrinsic* musculature does not directly contribute to make up the *intrinsic* architecture, it is logical to suggest that such functions are likely to be performed by the *intrinsic* musculature through specialized structures controlling the tubal lumen such as annular systems of

fiber bundles which surround the loop elbows, characteristic of the irregular course of the salpinx in this species. One may, therefore, reasonably assume the existence of a direct control of the *extrinsic* musculature over the *intrinsic* musculature in type 2 salpinxes (rabbit, ewe, sow, cow and woman). This supports the theory (Blandau 1969, 1973) that the *extrinsic* musculature has a primary role in the transport of gametes besides the pick-up of the oocyte from the ovary surface and the "tube locking" phenomenon.

It is widely accepted that myosalpinx contractions propagate randomly, producing a backward-forward egg motion (Daniel et al., 1975a,b; Talo and Hodgson, 1978) and are transmitted, usually over short distances, from different pace-maker sites (Talo and Pulkinen, 1982). These data were also confirmed by recording the random myoelectrical activity of the tube (Daniel et al., 1975a; Hodgson et al., 1977; Hodgson and Talo, 1978; Talo and Hodgson, 1978). A plexiform structure of myosalpinx, owing to the uneven distribution of SMC fibers, rather than originating a series of regular contraction waves, is more likely to produce random contraction waves. Therefore, the myosalpinx architecture provides an anatomical basis for a model of random tubal egg transport characterized by pendular "backward-forward" movements. These, in fact, resulting from contractions propagating for longer distances along the tube in one or other direction, can become asymmetric and unbalanced in either a pro or anti-uterine direction (Verdugo et al., 1980; Talo and Pulkinen, 1982; Verdugo, 1982). Furthermore, the hormones can control both the frequency and distance of propagation of myotubal contraction (Talo and Hogson, 1978), thus affecting the rate of gamete transport throughout the tube (Hodgson and Talo, 1978). Our observations show that the myosalpinx architecture - unlike that of hollow organs with geometrically arranged musculature (e.g. gut) in which the orthogonal disposition of SMC is related to generate and to co-ordinate peristaltic movements in an antagonistic manner - is similar to that of other hollow organs with plexiform musculature (e.g. gall bladder). The contraction of such a plexiform SMC structure (Hodgson et al., 1977) may deform the tube wall generating a stirring process within the tubal lumen. By such a stirring movement the contact between hormones and nutrients contained in the tubal lumen, and gametes, zygotes and embryos is intensified, resulting in a correct fertilization and early embryo development (Motta et al., 1994a,b, 1995, 1998, 1999). These phenomena can explain why the decrease in the tube length may cause a decrease in the percentage of pregnancies (Silber et al., 1980; McComb et al., 1979, 1981).

In conclusion, recent anatomical models of the 3-D organization of the myosalpinx, integrated, in some cases, with classical data, serve to better explain important aspects of the Fallopian tube's physiology such as the propagation of electrical activity, motility and tubal transport that, as recorded in the early literature, were rather inconsistent. They also allowed us

to hypothesize a new function for tubal contraction. Our concluding opinion is that further investigations in this field (following the above guideline) may provide new important insight regarding the unique role played by tube in the complex fertility process.

References

- Andersen D.H. (1927). Lymphatic of the Fallopian tube of the sow. *Contrib. Embriol. Carneg. Instn.* 19, 135-148.
- Andersen D.H. (1928). Comparative anatomy of the tubo-uterine junction. *Histology and physiology in the sow. Am. J. Anat.* 42, 255-305.
- Beck L.R. and Boots L.R. (1974). The comparative anatomy, histology and morphology of the mammalian oviduct. In: *The oviduct and its functions.* Johnson A.D. and Foley C.W. (eds). Academic Press. New York. London pp14-16.
- Bignardi C. (1948). Sull'anatomia microscopica della tuba uterina dei mammiferi domestici. *Biol. Lat.* 1, 651-687.
- Blandau R.J. (1945). On the factors involved in sperm transport through the cervix uteri of the albino rat. *Am. J. Anat.* 77, 253-272.
- Blandau R.J. (1969). Gamete transport-comparative aspects. In: *The mammalian oviduct.* Hafez E.S.E. and Blandau R.J. (eds.) University of Chicago Press. Chicago. pp129-162.
- Blandau R.J. (1973). Gamete transport in the female mammal. In : *Handbook of physiology. Section 7. Endocrinology II.* Greep R.O. and Astwood E.B. (eds) American Physiological Society. Washington. pp 153-163.
- Brosens I. and Gordon A.G. (1990). *Tubal infertility.* Lippincott Co. Philadelphia. USA. pp 2-11.
- Brundin J. (1965). Distribution and function of adrenergic nerve in the rabbit Fallopian tube. *Acta Physiol. Scand.* 66 Suppl. 259, 1-57.
- Brundin J., Fredricsson B., Norberg K.A. and Swedin G. (1969). The Sympathetic innervation of the oviduct in the rat. *Acta Physiol. Scand.* 75, 69-72.
- Daniel E.E., Posey V.A. and Paton D.M. (1975a). A structural analysis of the myogenic control systems of the human Fallopian tube. *Am. J. Obstet. Gynecol.* 121, 1054-1066.
- Daniel E.E., Lucien P., Posey V.A. and Paton D.M. (1975b). A functional analysis of the myogenic control system of the human fallopian tube. *Am. J. Obstet. Gynecol.* 121, 1046-1053.
- David A. and Czernobilsky B. (1968). A comparative histological study of the uterotubal junction in the rabbit, Rhesus monkey and human female. *Am. J. Obstet. Gynecol.* 101, 417-421.
- Edgard D.G. and Asdell S.A. (1960). Spermatozoa in the female genital tract. *J. Endocrinol.* 21, 321-326.
- Einarsson S., Jones B., Larsson K. and Viring S. (1980). Distribution of small- and medium-sized molecules within the genital tract of artificially inseminated gilts. *J. Reprod. Fertil.* 59, 453-457.
- Fawcett D. W. (1986). *A textbook of histology.* Bloom and Fawcett. WB Saunders Company. Philadelphia. pp 874-877.
- Ferraris F. (1947). Ricerche sull'architettura della tonaca muscolare delle vie genitali della donna. *Ann. Ostetr. Ginecol.* 69, 3-22.
- Fujii S., Konishi I., Katabuchi H. and Okamura H. (1990). Ultrastructure of smooth muscle tissue in the female reproductive tract: uterus and oviduct. In: *Ultrastructure of smooth muscle.* Motta P.M. (ed). Kluwer Academic Publishers. Boston. The Hague. pp 197-220.
- Fumagalli Z. (1949). Questioni attuali di morfologia nel campo delle vie genitali della donna. *Biologica Latina* 3, 422-453.

A new classification of Fallopian tube based on its myoarchitecture

- Gosling J.A. (1979). The structure of the bladder and urethra in relation to function. *Urol. Clin. North Amer.* 6, 31-38.
- Hartman C.G. and Ball J. (1930). On the almost instantaneous transport of spermatozoa through the cervix and uterus of the rat. *Proc. Soc. Exp. Biol. Med.* 28, 312-314.
- Hodgson B.J. and Talo A. (1978). Spike bursts in rabbit oviduct: II. Effects of estrogen and progesterone. *Am. J. Physiol.* 234, E439.
- Hodgson B.J., Talo A. and Pauerstein C.J. (1977). Oviductal ovum surrogate movement interrelation with muscular activity. *Biol. Reprod.* 16, 394-396.
- Horstmann E. and Stegner H.E. (1966). Tube, Vagina und Aussere Weibliche Genitalorgane. Die Muskulatur der Eileiters und Seiner Umgebung. In: *Handbuch der mikroskopischen Anatomie des Menschen*. Vol. VII/3. von Mollendorff W. (ed). Springer. Berlin. Heidelberg. New York. pp 63-81.
- Hunter R.H.F. (1973). Transport, migrations and survival of spermatozoa in the female genital tract: species with intra-uterine deposition of semen. In: *Sperm Transport, Survival and Fertilising Ability*. Hafez E.S.E. and Thibault C. (eds). INSERM. Paris. pp. 309-342.
- Hunter R.H.F. (1977). Function and malfunction of the Fallopian tubes in relation to gametes, embryos and hormones. *Eur. J. Obstet. Gynecol. Reprod. Biol.* 7, 267-283.
- Hunter R.H.F. (1986). Peri-ovulatory physiology of the oviduct, with special reference to sperm transport, storage and capacitation. *Dev. Growth Differ.* 28 (suppl.), 5-7.
- Hunter R.H.F. (1987a). Peri-ovulatory physiology of the oviduct, with special reference to progression, storage and capacitation of spermatozoa. In: *New horizons in sperm cell research*. Mohri H. (ed). Jpn. Sci. Soc. Tokyo. pp. 31-45.
- Hunter R.H.F. (1987b). Human fertilisation in vivo, with special references to progression, storage and release of competent spermatozoa. *Human Reprod.* 2, 329-332.
- Hunter R.H.F. (1988). Transport of embryos to the uterus: Normal and abnormal timing. In: *The fallopian tubes. Their role in fertility and infertility*. Hunter R.H.F. (ed). Springer-Verlag. Berlin. pp 127-137.
- Hunter R.H.F. and Hall J.P. (1974). Capacitation of boar spermatozoa: synergism between uterine and tubal environments. *J. Exp. Zool.* 188, 203-214.
- Hunter R.H.F., Cook B. and Poyser N.L. (1983). Regulation of oviduct function in pigs by local transfer of ovarian steroids and prostaglandins: a mechanism to influence sperm transport. *Eur. J. Obstet. Gynecol. Reprod. Biol.* 14, 225-232.
- Hunter R.H.F., Fléchon B. and Fléchon J.E. (1987). Pre- and peri-ovulatory distribution of viable spermatozoa in the pig oviduct: a scanning electron microscope study. *Tissue Cell* 19, 423-436.
- Kipfer K. (1950). Das Musculature der Tuba uterina als funktionelles system. *Acta. Anat.* 9, 35-56.
- Kushiya I. (1968). An electron microscope study of the muscular coats in the Ampulla of the rabbit oviduct, with special reference to the neuromuscular relationship. *J. Electron Microsc.* 17, 127-138.
- Low N.F. (1989). Microdissection by ultrasonication for scanning electron microscopy. In: *Cells and tissues: a Three-dimensional approach by modern techniques in microscopy*. Progress in clinical and biological research. Vol. 295. Motta P.M. (ed). Alan R. Liss Inc. New York. pp 571-580.
- Mann T., Polge C. and Rowson L.E.A. (1956). Participation of seminal plasma during the passage of spermatozoa in the female reproductive tract of the pig and horse. *J. Endocrinol.* 13, 133-140.
- MacPherson B.R., Yiu V., Lee W. and Scott G.W. (1986). A scanning electron-microscopic study of the muscle layer of the canine gallbladder. *Acta Anat.* 127, 59-64.
- McComb P. and Gomel V. (1979). The influence of fallopian tube length on fertility in the rabbit. *Fertil. Steril.* 31, 673-676.
- McComb P., Boer-Meisel M. and Gomel V. (1981). The influence of fallopian tube ampullary length on the fertility of the rabbit. *Int. J. Fertil.* 26, 30-34.
- Motta P.M., Pereda J., Nottola S.A. and Familiari G. (1994a). Ultrastructural changes of human cumulus oophorus during fertilization and zygote segmentation. In: *Perspectives on assisted reproduction*. Frontiers in endocrinology. Vol. 4. Mori T., Tominaga T., Aono T. and Hiroi M. (eds). Serono Symposia. Raven Press Books Ltd. New York. pp 89-95.
- Motta P.M., Makabe S., Naguro T. and Correr S. (1994b). Oocyte follicle cell association during development of the human ovarian follicle. A study by high resolution scanning electron microscopy. *Arch. Histol. Cytol.* 57, 369-394.
- Motta P.M., Nottola S.A., Pereda J., Familiari G. and Croxatto H.B. (1995). Ultrastructure of human cumulus oophorus: a transmission electron microscopic study on oviductal oocytes and fertilized eggs. *Human Reprod.* 10, 2361-2367.
- Motta P.M., Makabe S., Nottola S.A., Macchiarelli G., Familiari G. and Correr S. (1998). Morphodynamic events of human oocytes during folliculogenesis and in the extraovarian microfollicular unit. *Assisted Reproduction Rev.* 8, 205-216.
- Motta P.M., Nottola S.A., Familiari G., Macchiarelli G., Correr S. and Makabe S. (1999). Structure and function of the human oocyte-cumulus-corona cell complex before and after ovulation. *Protoplasma* 206, 270-277.
- Muglia U., Vizza E., Correr S., Germanà G. and Motta P.M. (1991a). Architecture of the myosalpinx of the isthmus in the guinea pig by means of scanning electron microscopy. *Acta Anat.* 142, 171-173.
- Muglia U., Vizza E., Correr S., Germanà G. and Motta P.M. (1991b). The three-dimensional architecture of the myosalpinx in the rabbit as revealed by scanning electron microscopy. *J. Submicrosc. Cytol. Pathol.* 23, 525-532.
- Muglia U., Vizza E., Macchiarelli G., Germanà G. and Motta P.M. (1992). The three-dimensional architecture of the myosalpinx in mammals: an anatomical model for a functional hypothesis. *Arch. Histol. Cytol.* 55, 171-181.
- Muglia U., Vizza E., Correr S., Germanà G. and Motta P.M. (1996a). The three-dimensional architecture of the myosalpinx in the rat (*Rattus norvegicus*) as revealed by scanning electron microscopy. *Histol. Histopathol.* 11, 873-880.
- Muglia U., Germanà A., Laurà R., Germanà G. and Motta P.M. (1996b). The three-dimensional architecture of the myosalpinx in the ewe as revealed by scanning electron microscopy. *Arch. Histol. Cytol.* 59, 331-338.
- Muglia U., Germanà A., Abbate F., Germanà G. and Motta, P.M. (1997a). The three-dimensional architecture of the myosalpinx in the cow as revealed by scanning electron microscopy. *J. Submicrosc. Cytol. Pathol.* 29, 201-207.
- Muglia U., Abbate F., Correr S., Germanà G. and Motta P.M. (1997b). The architecture of the myosalpinx in the sow as revealed by scanning electron microscopy. *Eur. J. Obstet. Gynecol. Reprod. Biol.* 74, 93-98.
- Nilsson O. and Reinius S. (1969). Light and electron microscopic structure of the oviduct. In: *The mammalian oviduct*. Hafez E.S.E.

A new classification of Fallopian tube based on its myoarchitecture

- and Blandau R.J. (eds). University of Chicago Press. Chicago. pp 57-83.
- Pauerstein C.J. and Eddy C.A. (1979). The role of the oviduct in reproduction; our knowledge and our ignorance. *J. Reprod. Fertil.* 55, 223-229.
- Pauerstein C.J., Alexander F.R.W., Mobley J.A. and Fremming B.D. (1970). Comparative anatomy of inner longitudinal layer of oviductal isthmus. *Obstet. Gynecol.* 35, 504-512.
- Pauerstein C.J., Hodgson B.J. and Kramen M.A. (1974). The anatomy and physiology of the oviduct. In: *Obstetrics and gynaecology*. Wynn R.M. (ed). Appleton-Century-Crofts. New York, USA. pp 137-201.
- Polge C. (1978). Fertilization in the pig and horse. *J. Reprod. Fertil.* 54, 461-470.
- Rigby J.P. (1967). The cervix of the sow during oestrus. *Vet. Rec.* 80, 672-675.
- Schilling E. (1962). Untersuchungen über den Bau und die Arbeitweise Eileiters vom Schaf und Rind. *Z. Veterinär med.* 9, 805-816.
- Silber S.J. and Cohen R. (1980). Microsurgical reversal of female sterilization: the role of tubal length. *Fertil. Steril.* 33, 598-601.
- Stange H.H. (1952a). Zur funktionellen Morphologie des Fimbrienendes der menschlichen Tube und des Epoophoron. *Arch. Gynak.* 182, 77-103.
- Stange R.H. (1952b). Comparative morphologic studies on human Fallopian tube in extreme functional states: question of existence of infundibular sphincter. *Z. Gynakol.* 74, 1176-1198.
- Tachibana S., Takeuchi M. and Uehara Y. (1985). The architecture of the musculature of the guinea-pig ureter as examined by scanning electron microscopy. *J. Urol.* 134, 582-586.
- Takahashi-Iwanaga H. and Fujita T. (1986). Application of an NaOH maceration method to a scanning electron microscopic observation of Ito cells in the rat liver. *Arch. Histol. Jpn.* 49, 349-357.
- Talo A. and Hodgson B.J. (1978). Electrical slow waves in oviductal smooth muscle of the guinea pig, mouse and the immature baboon. *Experientia* 34, 198-205.
- Talo A. and Pulkkinen M.O. (1982). Electrical activity in the human oviduct during menstrual cycle. *Am. J. Obstet. Gynaecol.* 142, 135-147.
- Uehara Y., Takashi F., Nakashiro S. and de San Z. (1990). Morphology of smooth muscle and its diversity as studied with scanning electron microscopy. In: *Ultrastructure of smooth muscle*. Motta P.M. (ed). Kluwer Academic Publishers. Norwell. pp 119-136.
- Verdugo P. (1982). Stochastic analysis of ovum transport: the effect of prostaglandin E2. *Cell. Motility* 1(suppl.), 85.
- Verdugo P. (1986). Functional anatomy of the Fallopian tubes. In: *Infertility: Male and female*. Vaclav I. and Lunenfeld B. (eds). Churchill Livingstone. London. pp 26-56.
- Verdugo P., Rumery R. and Tam P.Y. (1980). Hormonal control of oviductal ciliary activity: effect of prostaglandins. *Fertil. Steril.* 33, 193-196.
- Vizza E., Muglia U., Macchiarelli G., Baschieri L., Pasetto N. and Motta P.M. (1991). Three-dimensional architecture of the human myosalpinx isthmus. Scanning electron microscopy after NaOH digestion and ultrasonic microdissection. *Cell Tissue Res.* 226, 219-221.
- Vizza E., Correr S., Muglia U., Marchioli F. and Motta P.M. (1995). The three-dimensional organization of the smooth musculature in the Ampulla of the human Fallopian tube: a new morpho-functional model. *Human Reprod.* 10, 2400-2405.
- Vizza E., Heyn H., Magos A.L., Muglia U., Sbiroli C. and Motta P.M. (1997). Smooth muscle cells and extracellular fibrillar matrix of the human myometrium and myosalpinx studied by scanning electron microscopy after alkali maceration. In: *Recent advances in microscopy of cells, tissues and organs*. Motta P.M. (ed). A. Delfino Editore. Rome. pp 527-534.
- Weeth H.J. and Herman H.A. (1952). A histological and histochemical study of the bovine oviducts, uterus and placenta. *Res. Bull. Univ. Missouri, Columbia. MO.* 501.
- Williams J.W. (1891). Contributions to the normal and pathological histology of the fallopian tubes. *Am. J. Med. Sci.* 102, 377-386.
- Woodruff J.D. and Pauerstein C.J. (1969). The fallopian tube. Structure, function, pathology and management. Williams & Wilkins. Baltimore, MD, USA.
- Wrobel K., Kujat R. and Fehle G. (1993). The bovine tubouterine junction: general organization and surface morphology. *Cell Tissue Res.* 271, 227-239.

Accepted July 17, 2000