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# The luminal aspect of intrarenal arteries and veins in the rat as revealed by scanning electron microscopy

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**Summary.** The luminal aspect of intrarenal arteries and veins in the rat has been investigated by scanning electron microscopy (SEM). The endothelium of the intrarenal arteries consists of spindle-shaped cells and forms longitudinally running ridges which correlate with the folding pattern of the underlying internal elastic lamina. Intraarterial "cushions" were found at the origins of afferent arterioles from arcuate arteries and along the entire course of interlobular arteries. The intrarenal veins are made up of a thin, extensively fenestrated epithelium equal to that of peritubular capillaries. The outer aspect of the endothelium contacts adjacent tubules as closely as the capillaries proper. Thereby, the luminal aspect of the veins exhibits a striking "tubule relief" created by the underlying tubules. This wall structure of the intrarenal veins suggest that diameter and shape of the veins are probably highly dependent on the surrounding interstitial pressure.

**Key words:** Intrarenal arteries – Intrarenal veins – Intraarterial cushions – Renal blood flow – SEM

## Introduction

Renal circulation and its regulation are subject to intensive research. The relevance of certain structural features of intrarenal vessels, such as the intraarterial cushions and the capillary-like wall structure of the intrarenal veins is not fully understood. The present SEM-study provides data about the luminal aspects of intrarenal arteries and veins in the rat. These data emphasize the particular character of intrarenal vessels and its potential relevance in renal blood flow regulation.

## Materials and methods

The kidneys of 12 female Munich-Wistar rats (Ivanovas, Kisslegg, body weight 150 g) were prepared for SEM. The animals had no food for 24 h prior to perfusion, but had free access to water. After anesthesia (0.2 ml/100 g BW Inactin intraperitoneally) an osmotic diuresis was induced by the intravenous infusion (jugular vein) with a volume of about 7% of body weight of a 10% mannitol solution within 20 min. Thereafter the abdomen was opened, the abdominal aorta surgically exposed and cannulated below the renal arteries.

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To rinse the vasculature, an oxygenated 0.9 M NaCl solution containing $CaCl_2 \cdot H_2O$ (0.33 g/l), procain-HCl (5 g/l), polyvinylpyrrolidone (25 g/l), and liquemin (1 ml/l corresponding to 5000 USP-U heparin/l) was used. This solution had an osmolality of 350 mosmol, a pH of 7.3, and a temperature of 37° C. Perfusion pressure was 150 mm Hg. Following the rinse, total body perfusion was performed with a fixative solution containing 1.5% glutaraldehyde and 1.5% formaldehyde in 0.1 M cacodylate buffer. The solution was supplemented with 0.66 g/l $CaCl_2 \cdot 2H_2O$, 0.5 g/l picric acid, and 25 g/l polyvinylpyrrolidone (MW 40000) and had a total osmolality of 820 mosmol. Thereafter the kidneys were removed and immersed in the fixative solution for 24 h. Small cubes of tissue were prepared and thoroughly washed in 0.1 M cacodylate buffer. Postfixation was carried out for 1 h in a solution of 1% osmium tetroxide in 0.1 M cacodylate buffer. Dehydration was accomplished in graded ethanols and then the tissue was subjected to critical-point drying using $CO_2$. The dried specimens were mounted on aluminium stubs with silver conductive paint, sputter-coated with gold (100 Å), and examined in a Philipscan 500 scanning electron microscope operating at 25 kV.

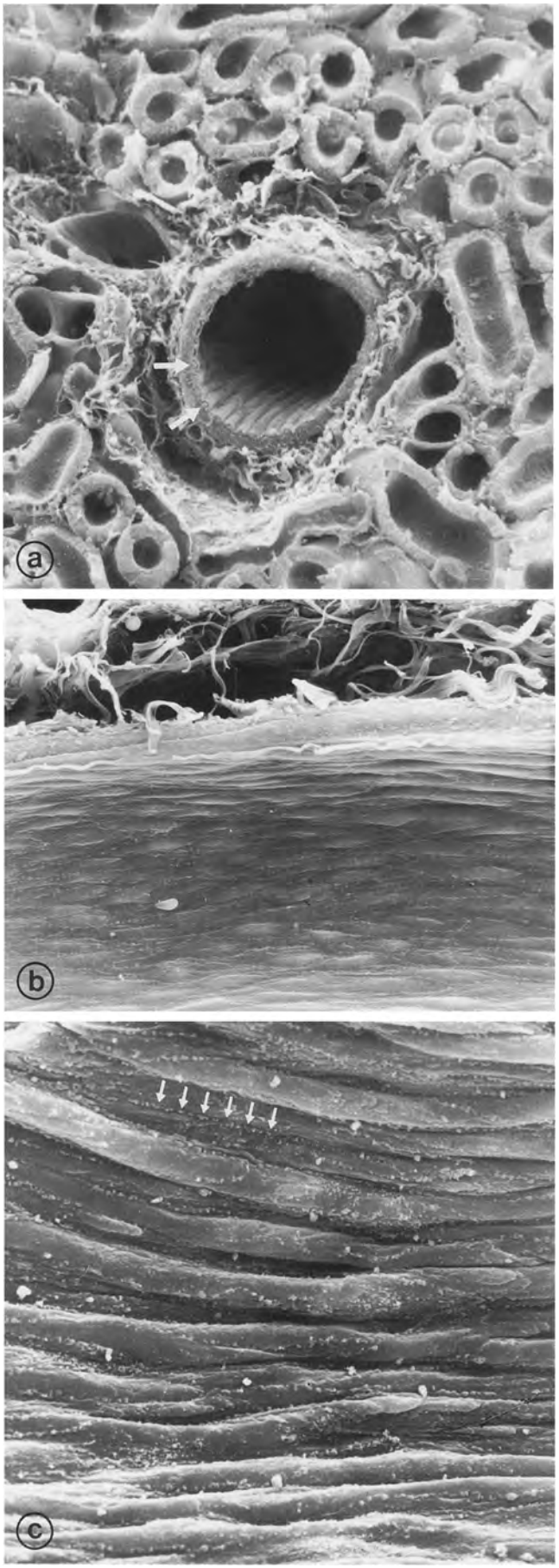
## Results

The various segments of intrarenal arteries and veins can easily be identified by their typical location. Interlobar, arcuate and interlobular arteries and veins are distinguished.

The arteries are embedded into the periarterial loose connective tissue which accompanies them as a circular layer. It is richly developed around interlobar and arcuate arteries, but decreases in thickness along interlobular arteries. It is composed of wavy collagen fibres. Wide open spaces are found between these fibres (Fig. 1a, b).

The endothelium of the arteries and afferent arterioles is folded into small ridges which run along the vessel axis (Figs. 1b, c; 2). The spindle-shaped endothelial cells are orientated in the same direction as the intimal folds; their nuclei bulge into the lumen. The luminal pattern of longitudinally running intimal folds corresponds to the folds of the underlying internal elastic lamina (Fig. 1a). The cell borders between individual endothelial cells are distinctly outlined by marginal cytoplasmic protrusions. Microvilli-like structures protrude from the cell surface, especially in the nuclear region (Fig. 1c).

At the exit of afferent arterioles, arterial cushions were regularly found in arcuate and along the entire course of




interlobular arteries (Fig. 3). The cushions are formed by two ridge-like endothelial folds which bulge into the lumen. Normally, they enclose the vessel orifice completely. In some cases they were found to be incomplete with an endothelial fold only on one side of the orifice.

The luminal aspect of the intrarenal veins has a striking appearance (Figs. 2, 4). The thin, venous endothelium covers adjacent tubules like a veil. Seen from inside a vein, one has the impression that the tubules are bulging into the lumen of the vein; they are clearly discernible through the venous wall. This particular relationship of the venous endothelium and the underlying tubules creates a very characteristic appearance of the luminal aspect of intrarenal veins: the walls of these veins exhibit a "tubule relief". This appearance is most expressive in arcuate and interlobular veins. Cross sectional profiles of arcuate and interlobular veins do not show a round profile, but resemble extremely wide peritubular capillaries traversing the cortex as tortuous channels (Fig. 4).

The orifices of capillaries and vasa recta which empty into the veins can clearly be recognized (Figs. 4, 5). They are always found in the niches of the vessel wall created by two bulging tubules. The orifices vary in size and shape. Often these orifices are traversed by endothelial strands (Fig. 5a). These strands are quite numerous and also found independent from capillary orifices. Generally, they bridge the niches between the protrusions created by underlying tubules.

The endothelial cells of the veins are of polygonal shape (Fig. 5a). The cells borders are distinct and the cell nuclei bulge into the lumen. Microvilli-like structures protrude from the cell surface. The endothelium of interlobar veins is only sparsely fenestrated. In contrast, arcuate and interlobular veins are equipped with a highly fenestrated capillary-like endothelium. The fenestrations are arranged in irregularly shaped "sieve plates" of extremely flattened endothelium (Fig. 5b). The fenestrated areas are separated by thicker cytoplasmic strands which converge towards the nuclear region.

## Discussion

This SEM view on to the inner surface of intrarenal vessels revealed some surprising results, while others are supporting to what is already known from TEM studies. The regular pattern of longitudinally running intimal folds of the intrarenal arteries is known from other studies in the kidney and at other sites (Jacobson et al. 1966; Bannister et al. 1975; Katora and Hollis 1976; Hollweg and Buss 1980; Tindall and Svendsen 1982). The controversy whether these intimal folds are an in vivo structure (Tindall and Svendsen

**Fig. 1. a** SEM of a cross sectioned arcuate artery. The periarterial loose connective tissue is well developed and forms a circular layer around the artery. The endothelium is folded into ridges which run along the vessel axis. The pattern of endothelial ridges corresponds to the undulating internal elastic lamina (*arrows*). × ~400. **b** Luminal aspect of an interlobar artery. The endothelial cells are spindle shaped with distinct cell borders. Above the vessel, the loose periarterial connective tissue is seen being composed of loosely arranged collagen fibres. × ~600. **c** Luminal aspect of an arcuate artery. The endothelium is folded into intimal ridges. The spindle shaped endothelial cells are distinctly outlined by rows of microvilli (*arrows*). × ~1500

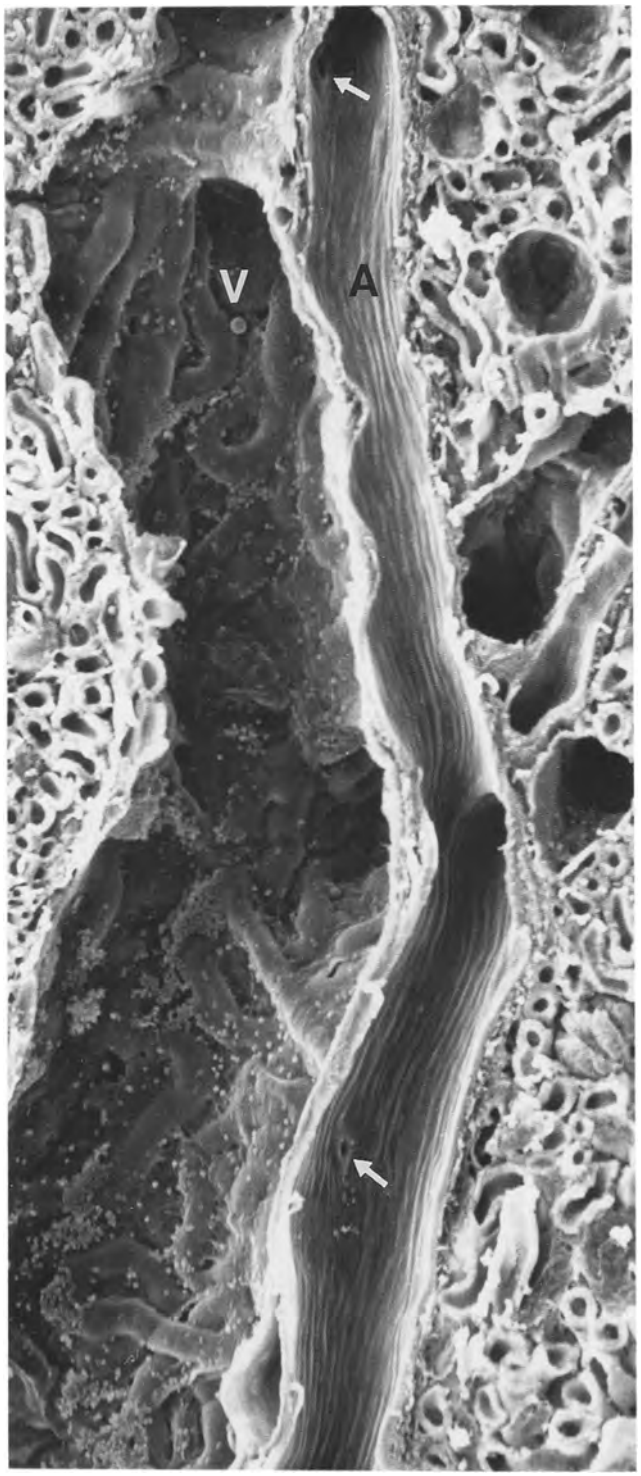



**Fig. 2.** Longitudinal section through an arcuate artery (*A*) and vein (*V*) which run together at the cortico-medullary border. The artery endothelium is folded into intimal ridges which form a regular pattern along the entire course of the vessel. Two intraarterial cushions are seen (*arrows*). The luminal aspect of the arcuate vein has a striking appearance, revealing the characteristic "tubule relief". The underlying tubules are bulging into the lumen, and are clearly discernible through the thin, endothelial coat. Conglomerates of erythrocytes stick to the venous wall

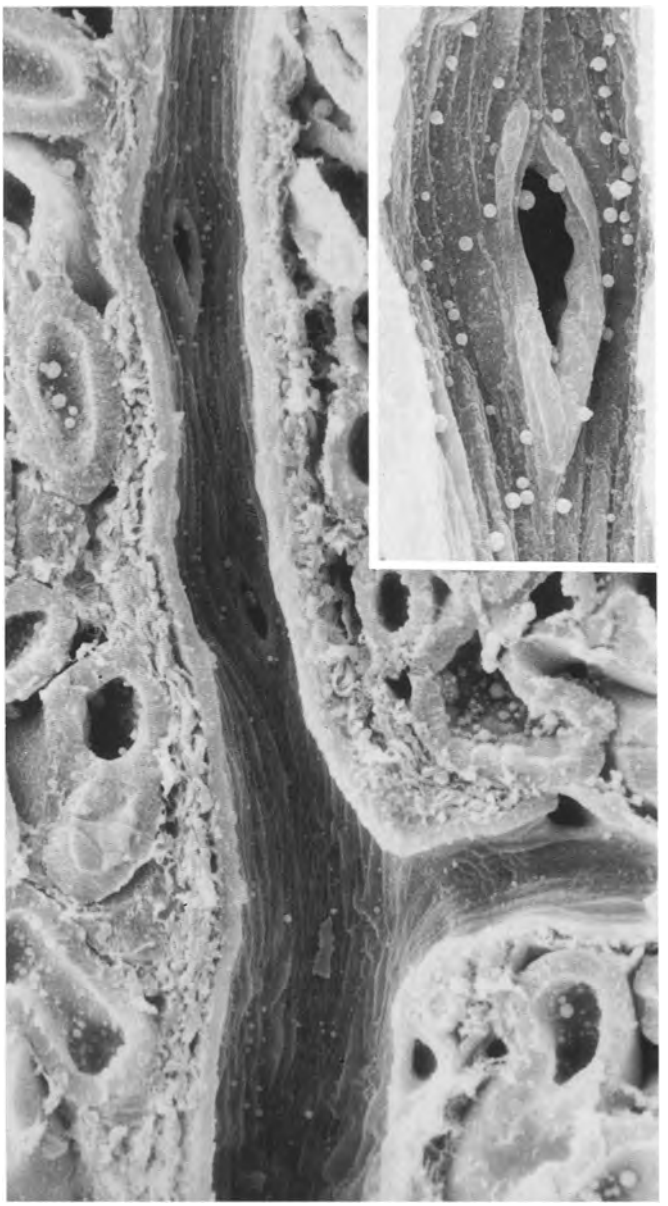


**Fig. 3.** Luminal aspect of a branching, interlobular artery. The endothelium is folded into longitudinally running ridges. Two arterial cushions are encountered which indicate the beginning of afferent arterioles. The inset shows a higher magnification of one of these cushions, which consists of two lateral folds enclosing the vessel orifice. × ~520, the inset × ~1600

1982; Lee and Chien 1979) or have to be regarded as an artefact created by an agonal contraction of the media muscles in response to fixation (Albert and Nayak 1976; Garbarsch et al. 1982) has not yet been settled. We, in agreement with the majority of studies, regard these folds as physiological structures and thus as a characteristic of the artery wall. A main argument in favour of this interpretation comes from the regularity of this folding pattern as seen in the scanning electron microscope. SEM allows studies of long, uninterrupted segments of arteries. The consistency of longitudinally running folds (Fig. 2) contradicts the suggestion that these folds might be created by uncontrolled agonal contractions. On the other hand it seems

clear from other studies (Lee and Chien 1979) that the height of these folds will vary with the degree of the distension of the vessel and/or the degree of the media contraction. In our material, we saw a good correspondence of the intimal folds with the folds of the internal elastic layer. As recently shown by in vivo studies (Steinhausen et al. 1986), the interlobar, arcuate and interlobular arteries respond to vasoactive substances (such as A II, AVP, ANF) by narrowing or widening the vessel lumen. Longitudinal folds appear to be the most appropriate to allow the adaptation of the endothelium to those acute changes in vessel diameter.

Intraarterial cushions are common in many species and organs (Shanklin and Azzam 1963a, b; Moffat 1959; Moffat 1969a, b; Fourman and Moffat 1971; Yohro and Burnstock 1973; Gorgas and Böck 1975; Velican and Velican 1977; Casellas et al. 1982), but there is still disagreement as to the functional relevance of these structures. With respect to the kidney they are found in some species (rat, cat, and dog), but not in others (rabbit, man; Fourman and Moffat 1971). Moreover, in the rat, they are described as being present exclusively at the origins of juxtamedullary afferent arterioles (Taggart and Rapp 1969; Moffat and Creasey 1971). Based on this distribution, it has been suggested that they might function as "plasma skimmers", supplying the juxtamedullary glomeruli and thus the renal medulla with blood of a low haematocrit (Fourman and Moffat 1961; Fourman and Moffat 1971). We, in agreement with Casellas and coworkers (1982), found cushions along the entire course of interlobular arteries, including the orifices to cortical glomeruli, without a predominance of the entrances to juxtamedullary afferent arterioles. Thus, from our findings, the intraarterial cushions do not seem to account for the low haematocrit of the vasa recta blood.

From the typical SEM aspect (two lateral ridges which run in the vessel axis and which cover to some extent the orifice from both sides), we suggest a passive role in adapting the orifice to different degrees of distention. Gorgas and Böck (1975) have presented convincing evidence that the arterial cushions at the origins of intercostal arteries in mice will undergo remarkable transformation when the parent arteries are dilated. We would like to suggest that during distention of the parent vessel, the cushion folds will be drawn into a tangential direction. Thereby the folds will come closer to the orifice, approaching a position just within the level of the orifice. As a consequence, the diameter of the orifice would be narrowed or at least dilated to a lesser degree compared to an unprotected orifice. From this point of view, the intraarterial cushions might contribute to stabilize the preglomerular blood flow by protecting the entrances to afferent arterioles from passive dilatations during sudden changes of the intraarterial pressure.

The fact that the intrarenal veins have an unusual, thin wall has been known since the description (based on a light microscopic study) by von Möllendorf (1930) and has been confirmed at the EM level by Dieterich (1978) and by Jones and O'Morchoe (1983). Similar to peritubular capillaries,

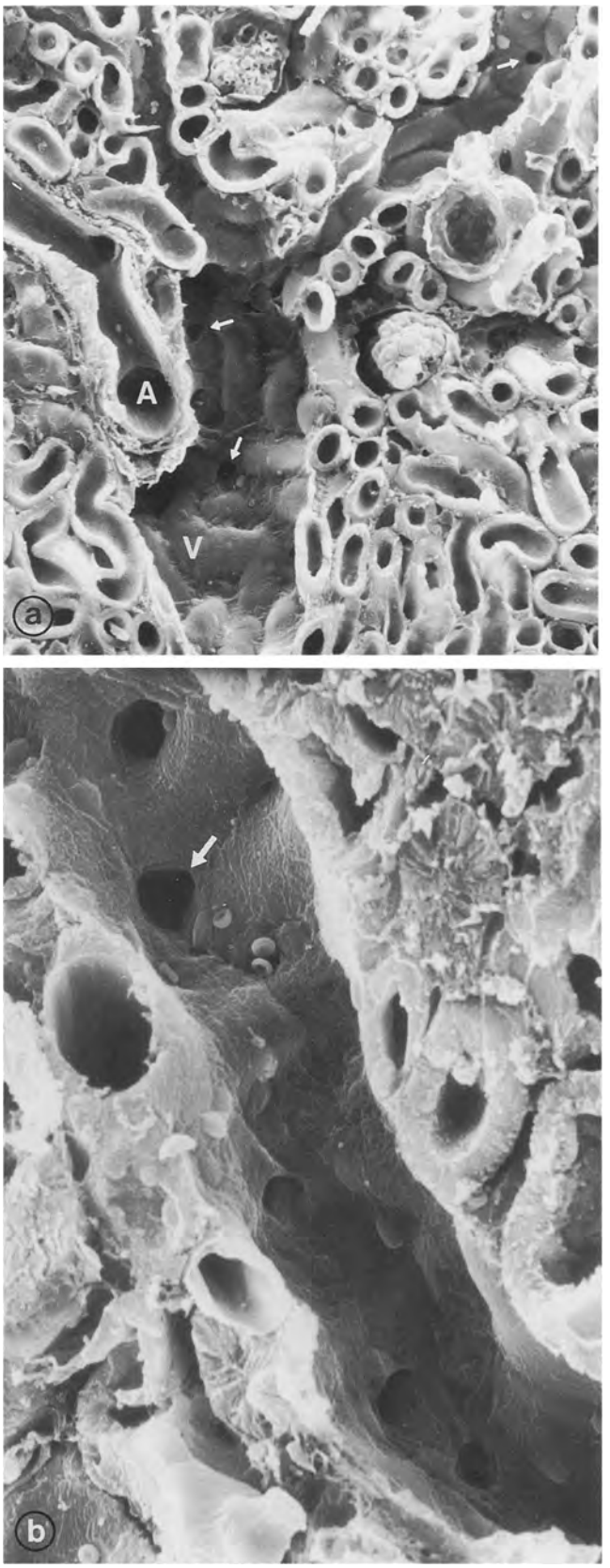



**Fig. 4. a** Longitudinal section through the beginning portion of an interlobular vein (*V*). Part of an interlobular artery (*A*) is also shown. The vein shows the typical aspect of the "tubule relief" created by the bulging of the underlying tubules. Several small vessels empty into the vein (*arrows*). The artery is embedded into the loose periarterial connective tissue. × ~200. **b** Luminal aspect of an interlobular vein. The orifices of emptying venous vasa recta or of capillaries are located in the niches between two bulging tubules (*arrows*). × ~800

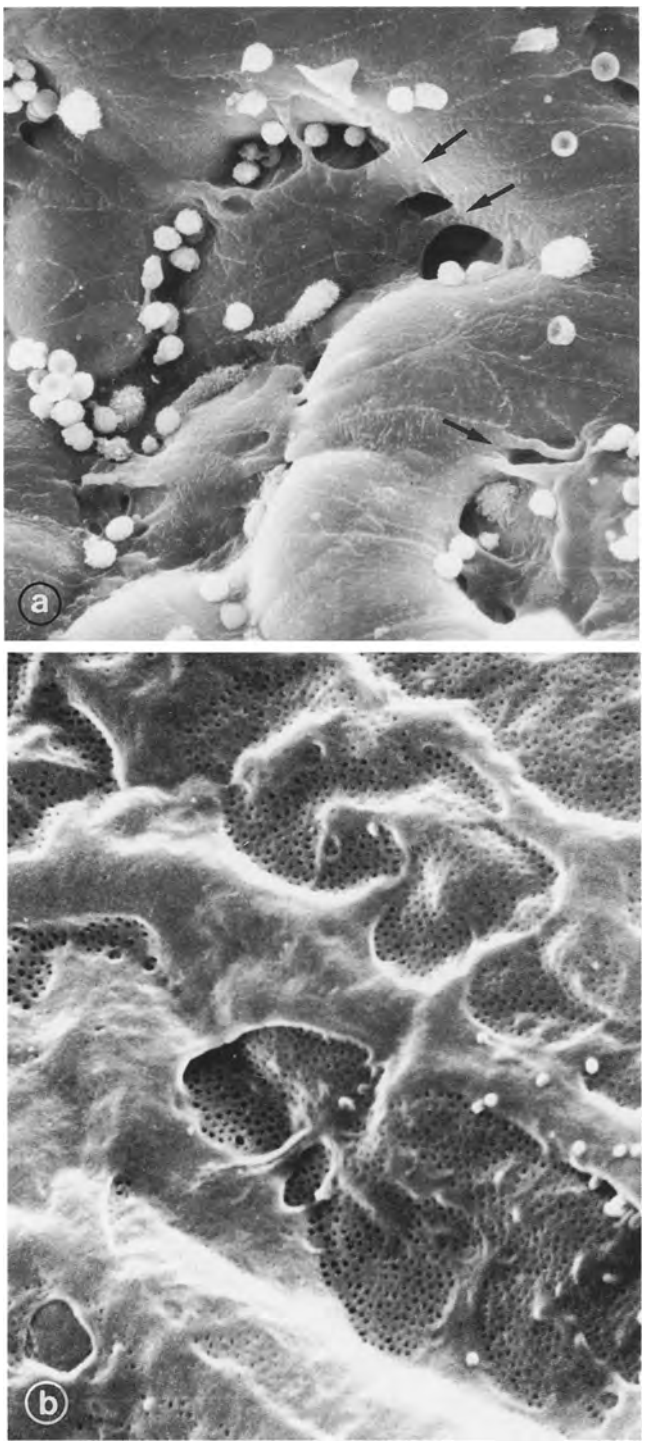



**Fig. 5.** **a** Luminal aspect of an arcuate vein. The venous endothelium covers an underlying tubule like a veil. Numerous small vessels empty into the vein; their orifices are located in the niches between the protruding tubules. Cytoplasmic strands (*arrows*) bridge over the niches which are between the protrusions of two underlying tubules. Often these strands traverse the orifice of an emptying vessel. Numerous erythrocytes and leucocytes stick to the wall. × ~1500. **b** This high power SEM of an interlobular vein shows the thin endothelium. The fenestrations are arranged in sieve plates separated by thicker parts of cytoplasm. × ~15000

the wall of the intrarenal veins is made up of only a thin, fenestrated endothelium. Since these veins come as closely as capillaries into contact with the outer aspect of tubules, it has been argued that in addition to a draining function the intrarenal veins play a reabsorptive role like do capillaries proper (Fourman and Moffat 1971; Kaissling and Kriz 1979; Jones and O'Morchoe 1983).

An additional relevance appears reasonable concerning the intrarenal distribution of kidney born substances. The intrarenal veins (especially interlobular and arcuate veins) accompany the intrarenal arteries by being apposed with part of their outer circumference to the periarterial loose connective tissue sheath (Kriz and Dietrich 1970; Swann and Normann 1970). These periarterial spaces have been interpreted as a compartment allowing the interstitial distribution of vasoactive substances (renin, angiotensin I, angiotensin II) generated within the kidney (Kriz 1987). In addition, vasoactive substances (e.g. prostaglandins, kallikrein, adenosine) may enter these spaces from the veins by passing through the endothelium. Thereby any vasoactive substance generated within the kidney and being taken up by the capillaries might leave the venous blood still within the kidney at the level of the interlobular and arcuate veins. This route provides the possibility for these substances to reach the intrarenal arteries from the periarterial side. By this route, kidney born vasoactive substances might have a chance to act on intrarenal arteries before leaving the kidney.

There is a further aspect concerning the delicate wall structure of the intrarenal veins which require a discussion. The intravenous pressure is found to be relatively high (roughly 10 mm Hg) and thus almost equal to the pressure found in the peritubular capillaries (Källskog et al. 1976). Somewhere along the arcuate or interlobar veins this pressure drops abruptly, a phenomenon known as vascular waterfall (Willassen and Ofstadt 1979; Permutt and Riley 1963; Aukland 1976). From the irregular shape of the intrarenal veins with extremely thin walls that follow the furrows and niches created by the tubules, it can be supposed that the intravenous pressure will reflect the renal interstitial pressure. Thus, blood flow through these venous vessels will be more dependent on the renal interstitial pressure than on the hydrostatic pressure. The high intrarenal pressure within the veins might be of some significance in protecting intrarenal veins and capillaries against changes in central venous pressure. A stable intrarenal pressure (interstitial, intracapillary, intravenous) is necessary for the stabilization of tubular reabsorption (Källskog et al. 1976). Thus, the intrarenal veins resemble capillaries and with respect to the Starling forces, the conditions for reabsorption in the intrarenal veins are the same as in the capillaries.

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