Centripetal Spread of Arterial Collateral Endothelial Cell Hyperplasia After Renal Artery Stenosis in the Rat

Norman K. Hollenberg and Teruo Odori

The factors responsible for collateral arterial growth after major artery occlusion remain obscure, despite their importance for tissue survival. An increase in endothelial cell labelling with tritiated thymidine, as an index of collateral arterial growth, occurs early after renal artery occlusion. Our working premise was that an increase in endothelial cell labelling would occur simultaneously throughout the length of the collateral arteries if biophysical factors related to blood flow were the responsible mechanism, because blood flow must be increased simultaneously throughout the length of the small, preformed collateral arterial vessels. On the other hand, if the information spread from the ischemic zone, one would anticipate centripetal spread of the endothelial cell hyperplasia in a retrograde direction from the ischemic zone. With the periureteric collateral arterial supply as the model, we performed serial studies of tritiated thymidine labelling following renal artery stenosis in the rat. As anticipated, endothelial cell labelling rose sharply within 24 to 48 hours, first evident in the area immediately adjacent to the renal hilum. Thereafter, a progressive, time-related centripetal gradient in endothelial cell tritiated thymidine labelling occurred (p < 0.01). These findings indicate that the factors responsible for endothelial cell hyperplasia are less related to blood flow in the lumen than to downstream, ischemic events. Although the mechanism responsible for the centripetal spread remains speculative, the communication system is likely to involve cell-to-cell contact in the vessel wall. (Circulation Research 1987;60:398-401)

Despite the importance of the collateral arterial supply for tissue survival following arterial occlusion, surprisingly little is known about the factors responsible for collateral arterial growth. One broad category of hypotheses is based on the possibility that biophysical factors related to the increase in flow they carry play a role. Several lines of evidence have also suggested that humoral factors participate in collateral vessel growth.2-3 We have shown that collateral arterial endothelial cell tritiated thymidine uptake occurs remarkably quickly, being evident within 24-48 hours after renal artery occlusion.4,5 This observation provides an approach to distinguishing between local biophysical factors in the arterial lumen or information emanating from the ischemic zone.

With a drop in the distal pressure following arterial occlusion, blood flow is increased simultaneously throughout the length of the small, preformed collateral arterial vessels. If biophysical factors related to blood flow were entirely responsible for endothelial cell hyperplasia, a simultaneous increase in endothelial cell mitosis would be anticipated throughout the length of the preformed collateral channels. On the other hand, if the information emanates from the ischemic zone, centripetal spread of the endothelial cell hyperplasia, in a retrograde direction, from the ischemic zone would be expected.

The periureteric vascular supply to the kidney following renal artery occlusion was used as the model for several reasons: the time course of the endothelial response in this system has been documented;4 the anatomic arrangement makes it unlikely that the surgery required to occlude the renal artery would damage the collateral supply through this route directly; and the kidney at one end and the bladder at the other provide convenient landmarks. Finally, the great length of this collateral supply simplified the identification of a gradient of endothelial cell labelling.

Materials and Methods

The studies were performed in 80 Sprague Dawley male rats weighing about 250 g. To occlude the renal artery, anesthesia was induced and maintained with ether, the left renal pedicle was approached through a flank incision, and about a 95% stenosis of the renal artery was induced by application of a silver clip over a 27 gauge needle employed at a stint.4,5 The clip was applied at the origin of the renal artery, adjacent to the aorta, where the artery is well separated from the renal vein and the ureter. Blueish discoloration of the kidney and softening were employed as additional, but crude, indices of significant but incomplete occlusion. Total occlusion of the renal artery characteristically produces a yellow-green color change. When the surgery was complete, the wound was closed with wound
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ranging from 0-3+. Zero and 1+ indicated, respect-
examined, an ordinal assessment system was adopted,
cause of the very low spontaneous turnover of endothe-
lumen with no evidence of cytoplasm medially. Be-
al when it was unequivocally at the surface of the
sections cut at each level (A0820 microtome) re-
xim
tered intraperitoneally, one hour apart. Two hours
thymidine injections (100 μCi/100 g body wt) were adminis-
ted intraperitoneally, one hour apart. Two hours
after the second injection, rats were killed, and blocks
including the kidney, the ureters with periuretic tis-
ue, and the bladder at the point of entry of the ureter
were excised on each side. The blocks were fixed in
10% buffered formalin for at least 24 hours prior to
processing automatically on the Auto Technicon tissue
processor (Technicon Co., Tarrytown, N.Y.) for de-
hydration in serially increasing ethanol concentrations.
Longitudinal blocks embedded in paraplast were made
of each periuretic area from the kidney to the blad-
er, and cross sections were cut at 16 equally spaced
intervals along the length of the ureter. Duplicate 5-
μm sections cut at each level (A0820 microtome) re-
sulted in 32 samples of each periureteric area for ex-
amination.

The sections were floated onto albumin-coated
slides, deparaffinized in xylene, hydrated in ethanol
and water, and air-dried in preparation for dipping.
Slides were dipped individually in Kodak NTB-2 nu-
clear track emulsion, and the dry slides were placed in
lightproof black boxes with a desiccating agent. A 12-
13-week exposure period was optimal for endothelial
labelling. The slides were developed with Kodak Dek-
tol and Rapid-Fix at 21°C and then stained with hema-
toxylin and eosin. After dehydration and clearing with
xylene, the slides were mounted with xylene with
Paragon "Supermount." Attention to detail was critical
because of the very low spontaneous turnover of vas-
cular endothelial cells, normally less than 0.1%. Label-
ed nuclei were assessed under oil immersion
light microscopy. A nucleus was considered endothel-
ial when it was unequivocally at the surface of the
lumen with no evidence of cytoplasm medially. Be-
cause of the very low spontaneous turnover of endothel-
ial cells and the large number of rats and sections
examined, an ordinal assessment system was adopted,
ranging from 0-3+. Zero and 1+ indicated, respect-
ively, either no or an occasional tritiated thymidine-
labelled endothelial cell. Conversely, 3+ indicated a
truly striking increase in endothelial cell turnover and
2+ a less striking but unequivocal increase over the
low, spontaneous normal turnover rate. In an earlier
assessment of vessel turnover in which formal label-
ling indices were defined by counting all positive and
negative endothelial cells, 1+ reflected a positive rate
of about 0.1-1.0% and 3+ a fiftyfold increase to 5-
6%. For presentation, 0 and 1+ were considered
"negative" and 2+ and 3+ "positive"; little was
 gained from the finer ordinal gradations.

In a subset, 5 rats in each group at day 0, 1, and 2
were selected at random, and the percent of thymidine-
labelling endothelial cells was estimated by counting
positive and negative cells. At least 400 cells were
counted in each ureteric quarter.

To assess the presence of a gradient in endothelial
tritiated thymidine uptake, data from the histological
sections were pooled to represent the quarter of the
ureter nearest the renal hilum, the quarter of the ureter
nearest the bladder, and the two intervening quarters.
A code number from a random number series was
assigned to each histologic section, and the code was
not broken until all the sections had been assessed
following radioautography.

Mean values have been presented with the mean ±
SEM as the index of dispersion. Where appropriate,
because multiple comparisons were made, statistical
probability was assessed by one way analysis of vari-
ance. Chi-square and the Fischer exact test were em-
ployed for nonparametric analysis of categorical infor-
mation. The null hypothesis was rejected for p < 0.05.

Results

The sham-operated rats showed no increase in tri-
tiated thymidine in endothelial cell uptake on any day
after the procedure (Table 1). The rats with renal artery
stenosis, on the other hand, showed the anticipated
brisk increase in endothelial cell tritiated thymidine
labelling (p <0.01), which was evident 48 hours after
renal artery stenosis and thereafter (Figure 1 and Table
1). Because the normal endothelial cell labelling index
ranges from 0.1-1.0%, a histologic section containing
more than one labelled endothelial cell was extremely
uncommon in normal animals and in the sham-operat-
ed group.

The periureteric vessels from rats with renal artery
stenosis showed clear evidence of centripetal spread of
increased tritiated thymidine endothelial cell labelling
from the portion nearest the kidney and extending with
time toward the region nearest the bladder (Figure 1).
Within 24 hours, the portion of the periureteric vessels
nearest the kidney showed a significant increase (p
<0.05), whereas there was no increase more distally.
By 48 hours, the endothelial cells nearest the renal
hilum were routinely positive for tritiated thymidine
labelling, and labelling was also evident, but less con-
sistent and less striking, in the mid-quarters (Table 1).
The portion nearest the bladder remained negative at
48 hours but became positive thereafter (Table 1).

Discussion

The working premise in this study was that the pat-
tern of collateral arterial endothelial cell hyperplasia
following renal artery occlusion could provide insight
into the responsible mechanisms. Renal artery stenosis induces an immediate, sharp drop in distal arterial blood pressure and, thus, an immediate increase in the pressure gradient along small, preformed arteries between the aorta and the intrarenal arterial tree. These presumably serve as the major potential collateral arterial pathway. One hypothesis to account for endothelial cell hyperplasia in this setting assumes that an increase in blood flow through such channels, perhaps acting via viscous drag at the plasma-endothelial cell interface, acts as a growth stimulus by analogy with the growth of vascular elements in an arteriovenous fistula. Indeed, the remarkable rapidity with which collateral arterial endothelial cell hyperplasia occurs following renal artery stenosis, a brisk response routinely being evident within 24–48 hours, made factors related to local biophysical forces an attractive possibility.

However, an unequivocal centripetal spread of the tritiated thymidine endothelial cell labelling was found. While no attempt was made to quantitate endothelial cell turnover, it was quite clear that the collateral vessels were growing very rapidly at that time and endothelial cell number must have been increasing. The response reflects true hyperplasia.

Local trauma related to the surgical procedure is an unlikely source of artifact because sham-operated rats did not show increased arterial thymidine labelling. Indeed, to the extent that removing the clip was traumatic, the region of the renal pedicle was subjected to more local trauma in sham-operated rats than in the rats in which the clip was left in place.

Two potential sources of bias were dealt with by the experimental design. First, rats were assigned to sham or stenosis groups and to days of follow-up before the surgical procedure on the basis of a coded random number. Thus, any bias created by events during the surgical procedure could not have contributed to the result. Second, assessment of radioautographs involves a subjective element, although the response is truly striking, but all assessments were made on a coded basis. The reader did not know whether the sections were made from the sham or stenosis group, the day of follow-up, or whether proximal or distal portions of the ureter were being evaluated by the assessment. Bias, therefore, could not have contributed to the finding of a coherent, progressive, time-related centripetal gradient in endothelial cell tritiated thymidine labelling.

Perhaps the most interesting question involves how the information spreads along the artery. Retrograde movement along the arterial lumen against blood flow

<table>
<thead>
<tr>
<th>Day</th>
<th>n</th>
<th>Near kidney</th>
<th>Proximal mid-quarter</th>
<th>Distal mid-quarter</th>
<th>Near bladder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% +</td>
<td>Median</td>
<td>% +</td>
<td>Median</td>
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<tr>
<td>A. Stenosis</td>
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</tr>
<tr>
<td>0</td>
<td>12</td>
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<td>0</td>
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<tr>
<td>1</td>
<td>12</td>
<td>33</td>
<td>0</td>
<td>9</td>
<td>0</td>
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<tr>
<td>2</td>
<td>12</td>
<td>100</td>
<td>++ +</td>
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<td>12</td>
<td>91</td>
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<td>75</td>
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<tr>
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<td>12</td>
<td>100</td>
<td>++ +</td>
<td>83</td>
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<td>B. Sham</td>
<td></td>
<td></td>
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<td>0–6</td>
<td>20</td>
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</tbody>
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0 = No evidence of increased labelling; ++ = unequivocal increase in labelling but not immediate in degree; ++ + = striking increase in labelling.
seems unlikely. It is difficult to imagine that forces involved in diffusion can overcome the vector created by inflowing arterial blood to create a concentration gradient up the arterial tree over 3–4 cm, as was involved in this model. Diffusion of some product of ischemia through the tissue planes is possible but also seems unlikely. We have shown that a vascular mitogen is found in high concentration in lymph draining an ischemic kidney, raising the possibility that major lymphatic channels draining an ischemic zone serve as the conduit for the stimulus. Periureteric lymphatic drainage of a mitogen could account for our surprising finding that basal layers of the ureteric epithelium become hyperplastic after ipsilateral renal arterial stenosis despite the fact that the urine does not contain a mitogen. The mitogen, however, appears to be a large molecule, and major lymphatics are normally not permeable to large molecules, a characteristic central to their primary role in draining proteins from the interstitium.

The most likely possibility involves cell-to-cell contact and communication. This phenomenon, clearly documented in a number of systems, operates in vascular elements as well. Ryan et al. described a similar gradient of endothelial cell division after the creation of an injury in an in vitro tissue culture of endothelial cells. Clearly, no ischemia was involved in that model. Although a number of chemical mediators responsible for communication via cell-to-cell contact have been identified, in general they have been smaller molecules than the vascular mitogen appears to be.

We have recently demonstrated centripetal spread of endothelial cell hyperplasia along the "feeder artery" to a malignant tumor in the rat, as the feeder vessel grows. It seems possible that the growth of a feeder vessel to a tumor and growth of a collateral arterial blood supply include a hyperplastic component that shares a common communication system and mediator. Arterial vessels also grow through unexplained mechanisms during embryogenesis and fetal growth. All three situations share a common feature: The metabolic demands of fetal growth, the metabolic demands of tumor growth, and the requirements of tissue rendered ischemic by arterial occlusion all induce hyperplasia of vascular elements of the local arterial supply. Whether or not identical factors are responsible in each case, insight into the responsible mechanisms for one is likely to provide insight into the responsible mechanisms for all. The control of vascular wall growth is likely to be complex. Endothelial cells synthesize a mitogen, the endothelial cell-derived growth factor. This factor or one like it may contribute to cell-to-cell communication in the hyperplastic response that characterizes collateral arterial growth.

References


KEY WORDS • tritiated thymidine • ischemia
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