Clinical progression of motor deficit hours or days after an ischemic episode in the central nervous system (CNS) has been termed "deteriorating stroke." The underlying pathophysiologic mechanisms of the deterioration after stroke are poorly understood in part due to lack of experimental models designed to focus on the deterioration.

Several studies suggest that a number of biochemical and metabolic events contribute to progressive and irreversible cell damage as well as to tissue hypoperfusion after ischemia. Recently, it was suggested that eicosanoids may be involved in the secondary damage observed during reperfusion of ischemic brain. These eicosanoids [prostaglandins (PGs), thrombox-

ane A$_2$ (TXA$_2$), and leukotrienes] are potent vasoactive substances that may be involved in regulation of blood flow, microvascular permeability, and inflammatory responses. Although there is considerable species and tissue variability in the response to eicosanoids, it is generally accepted that TXA$_2$ and PGI$_2$ have opposite effects on vascular tone and platelet aggregation and may be involved in the local regulation of blood flow. In all studies, TXA$_2$ is a potent vasoconstrictor and platelet aggregator, whereas PGI$_2$ generally produces vasodilation and inhibits platelet aggregation. PGE$_2$, however, has vasoconstrictor effects on cerebral vessels in rabbits and is involved in inflammatory responses.

The experiments presented in this study explored the potential role of some eicosanoids in a stroke model of progressive motor deterioration after acute ischemia. In this model, ischemia of the rabbit lumbar spinal cord is produced by ligation of the lower abdominal aorta. This model provides a unique opportunity to study motor function in conscious rabbits during ischemia and reperfusion.

We report studies that better characterize this deteriorating stroke model in view of the histopathology, edema formation, and tissue concentrations of PGI$_2$, TXA$_2$, and PGE$_2$. The data presented in this work indicate temporal histopathologic and edema changes associated with selective changes in eicosanoid production throughout the period of functional deterioration following lumbar spinal cord ischemia.
Surgical Preparation

Fifty-five male New Zealand albino rabbits (Hazleton Labs, York, Pa.) were anesthetized with 50 mg/kg i.m. ketamine hydrochloride and 40 mg/kg i.v. sodium pentobarbital. Under aseptic technique, a transperitoneal incision was made to expose the abdominal aorta, and a 0.75-mm o.d. polyethylene tubing was placed around the aorta distal to the renal arteries and was threaded through 2 6.0-mm diam. plastic buttons dorsal and ventral to the aorta to produce a snare ligature. To prevent movement through the incision site, the ligature was passed through a 6.25-mm o.d. vinyl guide tube that was sutured to the abdominal muscles. A custom-made canvas jacket was then placed around the rabbit to protect the incision site and the externally accessible ligature. The experiments reported were conducted according to the principles set forth in the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animals Resources, National Research Council, Department of Health, Education, and Welfare, National Institutes of Health publication number 85-23.

Induction of Experimental Ischemia

Ischemia was induced in the spinal cord using a modification of the stroke model described by Zivin and DeGirolami. Approximately 18 hours after surgery, when the rabbits were awake, the aorta was occluded for 25 minutes by pulling on the snare ligature and clamping with a pair of hemostat forceps. This period of occlusion produced paralysis of the hindlimbs in 95% of all control rabbits by 48 hours after reperfusion in the work of Faden and Jacobs. Motor function was also evaluated after 15 and 20 minutes of occlusion. After occlusion, the ligature was released and removed with the guide tube through the surgical site. A retaining suture that was placed through the abdominal muscles at surgery was then secured. Postoperative and treatment procedures included monitoring food and water intake, expressing the urinary bladder as needed (Crede’s maneuver), and neurologic scoring of hindlimb motor function. A control group consisted of normal or sham-operated rabbits that were not subjected to ischemia.

Neurologic Examination

Hindlimb motor function was graded at hourly intervals during the first 24 hours after occlusion. The following ordinal grading scale was used: 0, complete paralysis; 1, minimal functional movement, severe parasesis; 2, functional movement, cannot hop; 3, hopping, ataxia and parasesis; 4, hopping, mild ataxia and/or parasesis; and 5, normal. Rabbits were also categorized as hoppers (neurologic score of 3, 4, or 5) or nonhoppers (neurologic score of 0, 1, or 2). Two investigators evaluated the rabbits independently.

Physiologic Measurements

Mean arterial pressure (MAP) and heart rate (HR) were continuously measured via a catheter placed in an ear artery and connected to a Narco Bio-Systems Model 1500i pressure transducer (Houston, Tex.) coupled to a Narco Bio-Systems Model MK-JV physiograph. Core body temperature (T) was monitored via a rectal thermistor connected to a telethermometer (Yellow Springs Instruments, Inc., Yellow Springs, Ohio). PaO2, PaCO2, and pH were measured at T with an Instrumental Model 1303 automated blood gas analyzer (Dayton, Ohio).

Biochemical Measurements

At 5 and 30 minutes, 4, 18, and 24 hours after occlusion, rabbits were killed with 100 mg/kg i.v. sodium pentobarbital, and the spinal cord was rapidly removed from the spinal canal within 45 seconds and processed by slicing the lesion area for analysis of biochemistry by freezing on dry ice, edema by immersion in kerosene to prevent water evaporation, and histopathology by immersion fixation in 10% buffered formalin. Venous blood was collected in tubes containing 20 μL of 10-4 M indomethacin, centrifuged, and frozen for TXB2 and 6-keto-PGF1α analysis by radioimmunoassay (RIA).

TXB2 (the stable metabolite of TXA2), 6-keto-PGF1α (the stable metabolite of PGI2), and PGE2 were extracted from the spinal cord using a technique previously described. Tissue concentrations of these metabolites were determined by RIA using specific antibodies purchased from Dr. Lawrence Levine (Brandeis University, Waltham, Mass.) with cross-reactivity of <1.0% with other cyclooxygenase metabolites. [3H]TXB2, [3H]6-keto-PGF1α, and [3H]PGE2, 100-200 Ci/mmol, were purchased from New England Nuclear (Boston, Mass.). Samples were incubated with antibody and the corresponding radioligand for 18-24 hours at 4°C. To separate bound and free ligands, 200 μL of 1% activated Norit-GSX charcoal (Sigma Chemical Co., St. Louis, Mo.) coated with 0.1% dextran (Kodak, Rochester, N.Y.) was added to the sample and centrifuged at 1000g for 10 minutes. Five milliliters of Redisol scintillation fluid (Beckman, Palo Alto, Calif.) was added to the decanted sample and radioactivity was determined by liquid scintillation counting (Model 1218, LKB, Gaithersburg, Md.). The sensitivity of the assays was 16 pg/tube. Protein content of the sample was determined by the method of Lowry et al. Plasma concentrations of the metabolites TXB2 and 6-keto-PGF1α were determined with commercially available RIA kits from New England Nuclear.

Microgravimetry for Measuring Tissue Edema

To measure edema in different regions of the spinal cord, the specific gravity (SG) of 1-mm3 tissue segments (punches) was determined by means of a density gradient column according to a method previously described. Two solutions of different SG were prepared from kerosene and bromobenzene (SG = 0.79 and 1.49, respectively; Fisher Scientific, Silver Spring, Md.). A flask containing 200 ml of Solution A (SG = 0.975) was positioned to slowly siphon down...
43 cm of polyethylene tubing into a flask containing 200 ml of Solution B (SG = 1.065). As the two mixed, the mixture was siphoned down 40 cm of polyethylene tubing into the gradient column, which was constantly lowered to maintain a uniform gradient at the surface of the column. In this way, a linear density gradient ranging from SG = 1.065 to 1.020 was established, which encompasses the range of both normal and edematous spinal cord tissue. The column was allowed to stabilize for 1 hour and was then calibrated with 3-μl drops of a previously prepared graded series of NaCl solutions of known SG from SG = 1.025 to 1.057. The drops served as SG reference points and verified the linearity of the density gradient. If a correlation coefficient of r ≥ 0.995 was not reached, the column was discarded.

Immediately after the spinal cord was removed, a 1-mm slice was immersed in kerosene to prevent evaporation of water. Tissue punched from various regions of the spinal cord including the ventral horn (VH) gray matter, lateral (LW), dorsal column (DC), and ventral (VW) white matter tracts using a blunt 15-gauge needle was then carefully placed on top of the density gradient column. After 3 minutes, the samples reached a stable position within the column, and SG of the punches was measured in relation to the NaCl standards.

Light Microscopy for Determining Histopathologic Changes

After removal, the lumbar spinal cord was immersion-fixed in 10% formalin with 10% glycerin (Fisher Scientific) by vol. for at least 72 hours. The tissue was dehydrated in graded alcohols, embedded in paraffin (Fisher Scientific), and cut in 7-μm transverse sections with a Sorvall JB-4A rotary microtome (Wilmington, Del.). Sections were stained with hematoxylin and eosin (Fisher Scientific) and Luxol fast blue (Sigma Chemical Co.). The spinal cord lesions were evaluated by an investigator unaware of reperfusion time using the following criteria: 3, no lesion observed; 2, gray matter contained 1-10 necrotic neurons with ≤ 33% of the cross-sectional area involved; 1, gray matter contained 10-20 necrotic neurons with 33-66% of the cross-sectional area involved; and 0, gray matter contained >20 necrotic neurons with >66% of the cross-sectional area involved. Vacuolation of the neuropil was observed in most rabbits with lesions; however, vacuolation was not quantifiable or as sensitive an indicator as neuronal necrosis. Histopathologic changes following ischemic injury are fairly predictive of neurologic outcome and can be readily assessed using ordinal scoring methods.1319

Results

Neurologic Function

A clear correlation between the duration of ischemia and the functional outcome is presented in Figure 1A. Most rabbits subjected to 15, 20, or 25 minutes of ischemia regained hopping function by 4 hours after reperfusion but underwent deterioration of function sometime thereafter. The degree of motor deterioration depended on the duration of the ischemia, with rabbits in the 25-minute group most severely affected (Table 1). The 25-minute group was selected for fur-

Data Analysis

Data are presented as means ± SEM. Eicosanoid and tissue edema levels in ischemic rabbits were compared with normal rabbits using analysis of variance (ANOVA) followed by the Dunnet’s test.21 Physiologic data were evaluated by repeated-measures ANOVA.21 Eicosanoid concentrations in hopping and nonhopping rabbits were compared using Student’s t test. Frequency analysis was performed using Fisher’s exact probability test.22 Spearman’s rank correlation test was used to measure the association between neurologic and pathologic scores.22 Values for all of the above statistics were considered significant at p < 0.05.

Figure 1. Hindlimb motor function in rabbits. A. Response to duration of ischemia. Points are median neurologic scores. CTL, normal functional score prior to ischemia. Numbers of rabbits in parentheses. B. Effects of 25-minute aortic occlusion during the 24-hour postischemic period (0 hours). Circles are individual rabbit’s scores, and bars are median values. Neurologic scores were based on ordinal scoring methods (see “Materials and Methods”).
Table 1. Effect of Duration of Lumbar Spinal Cord Ischemia on Hindlimb Motor Function as Neurologic Score in Rabbits During Reperfusion

<table>
<thead>
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</table>

Neurologic scores during the 48-hour reperfusion period (see “Materials and Methods”). Numbers are percent of rabbits with each score. N, number of rabbits.

ther analysis because rabbits deteriorated from a hopping (Score 3, 4, or 5) to a nonhopping status (Score 0, 1, or 2).

Within 60 seconds of aortic occlusion, all rabbits had complete hindlimb paralysis, which remained for the duration of the 25-minute ischemic period. Ten rabbits were scored hourly during the 24-hour reperfusion period. Within 4 hours of reperfusion, 70% of the rabbits regained substantial hindlimb function and were capable of hopping (Figure 1B). However, 12–18 hours after reperfusion, a secondary decline in hopping function was observed. By 24 hours after reperfusion, 70% of the rabbits were unable to hop. Hindlimb function changed very little after 24 hours and never improved (unpublished results).

Physiologic Measurements

T, MAP, Pao₂, pH, and Paco₂ did not differ from control values during ischemia or the 24-hour reperfusion period (n = 5, Figure 2). HR increased significantly during early reperfusion but was within the physiologic range after 12 hours of reperfusion (repeated-measures ANOVA followed by Dunnett’s test, F = 2.956, p = 0.040, n = 5). The physiologic ranges for HR, T, MAP, Pao₂, pH, and Paco₂ were determined in resting, unrestrained rabbits (range = mean ± SD, n = 15).

Eicosanoid Tissue Concentrations

Five minutes after reperfusion (early phase), tissue TxB₂ concentration in the lumbar spinal cord increased almost threefold (ANOVA, F = 8.32, n = 31, p < 0.01; Figure 3). Concentrations of 6-keto-PGF₁₀, however, did not change during reperfusion. The increase in TxB₂, but not 6-keto-PGF₁₀, at 5 minutes led to a 2.5-fold increase in the TxB₂:6-keto-PGF₁₀ ratio (ANOVA, F = 7.16, n = 31, p < 0.01). Thirty minutes after reperfusion (early phase), PGE₂ concentra-
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EARLY PHASE

** 3.0

** TXB2 concentration and the TXB2/6-keto-PGF1α ratio were significantly higher at 5 minutes of reperfusion (early phase) than control (ANOVA followed by Dunnett's test, p<0.01). *TXB2 concentrations were also increased at 18 hours of reperfusion (late phase) (ANOVA followed by Dunnett's test, p<0.05).

LATE PHASE

Concentrations of PGE2 did not change during the late phase (Figure 4).

Assays for TXB2 and PGs were also performed on spinal cord T10-T12 segments, which did not include the ischemic lesion. No significant changes were observed at these sites, which demonstrates that the TXB2 and PG increases were confined to the ischemic zone (n = 40, Table 2). Plasma concentrations of TXB2 were not different from control levels (Table 3). Plasma 6-keto-PGF1α levels were not detectable.

Tissue Edema

A significant decrease in SG was observed as early as 30 minutes after reperfusion in both gray (VH) and white (DC and VW) matter (ANOVA; F = 11.58 for VH, F = 8.01 for DC, F = 9.12 for VW; n = 53,
EARLY PHASE  LATE PHASE

![Graph showing PGE2 concentrations in lumbar spinal cord of rabbits subjected to 25 minutes of ischemia via aortic occlusion](image)

**Figure 4.** PGE2 concentrations in the lumbar spinal cord of rabbits subjected to 25 minutes of ischemia via aortic occlusion. Number at the base of bars is the number of animals per group. *PGE2 concentration was significantly higher than control at 30 minutes after reperfusion (ANOVA followed by Dunnett’s test, p<0.05).

$p<0.01$ for each, Figure 6A). However, by 4 hours after reperfusion, tissue water content returned to near-normal levels in all regions. At 18 hours after reperfusion, a second decline in SG was first observed in VH, followed by a further decrease in SG at 24 hours in VH, DC, VW, and LW columns (ANOVA, $F = 3.49$ for LW, $n = 53$, $p<0.01$). The pattern of tissue water content changes appeared to follow the pattern of neurologic change during reperfusion (Figure 6B).

Therefore, we categorized rabbits as hoppers or non-hoppers and grouped the SG measurements. For non-hopping rabbits ($SG = 1.0378 ± 0.0006$), SG of VH was lower than that of hopping rabbits ($SG = 1.0411 ± 0.0004$) ($t$ test, $t = 4.27$, $n = 53$, $p<0.01$). SG of white matter tracts was also different between hopping and nonhopping rabbits ($t$ test; $t = 4.99$ for VW, $t = 3.55$ for DC, $t = 3.11$ for LW; $n = 53$, $p<0.01$ for each).

**Histopathologic Changes**

The major histopathologic changes observed after 25 minutes of ischemia in the rabbit spinal cord were neuronal necrosis and vacuolation of the neuropil (Figure 7). Neuronal necrosis was first observed in 43% of the rabbits 4 hours after reperfusion and was limited to the intermediate gray area. Eighteen hours after reperfusion, neuronal necrosis was present in the intermediate gray and DH areas, with occasional degenerate neurons in VH of all rabbits. In addition, vacuolation of the neuropil was observed in the intermediate gray and VH areas in 25% of the rabbits. At 24 hours after reperfusion, lesions were similar to those observed at 18 hours, although usually more severe; vacuolation of the neuropil was present in all rabbits (Figure 7).

Correlation between the histopathologic changes and hindlimb motor function changes was highly significant (Spearman’s rank correlation test, $r_s = 0.642$, $p<0.01$, $n = 23$; Table 4).

**Discussion**

A distinct advantage of the present model to study events after ischemia is that an integrated CNS function can be monitored. This model has characteristics similar to deteriorating stroke, which includes stroke-in-evolution. During reperfusion, 70% of the rabbits regained substantial motor function within 4 hours; however, over the next 20 hours, motor function stead-
The present study demonstrated that spinal cord concentrations of TXB2 in rabbits increased immediately on reperfusion, similar to reports of brain ischemia models in which TXB2 tissue concentration was temporarily elevated on reperfusion in several species. At 30 minutes after reperfusion, PGE2 concentrations were also increased, whereas TXB2 levels were decreased. The differential changes in eicosanoids in our model vary from recent studies in which reperfusion of ischemic gerbil and rat brain caused an immediate increase in all cyclooxygenase metabolites measured. In the rabbit model, only TXB2 was elevated while 6-keto-PGF1α was not changed. The selective increase in TXB2 may indicate that cellular elements which produce TXA2, e.g., platelets, macrophages, and neutrophils, are activated. The lack of increase in PGE2 immediately after reperfusion might be the result of inhibition of PGE-isomerase by the high arachidonic acid (AA) concentration in the tissue at this time. On consumption of much of the AA, PGE-isomerase activity is resumed, leading to PGE2 generation as seen 30 minutes after reperfusion. Since PGE2 has constrictor effects on rabbit CNS microvessels, elevated PGE2 levels may propagate the initial vasoconstriction produced by TXA2. The imbalance in the TXA2:PGE2 ratio could favor platelet aggregation and vasoconstriction, thus leading to further ischemic damage. This possibility is supported by studies showing that supplementing PGI2 together with blocking TXA2 formation protects CNS tissue from acute ischemic insults.

At 4 hours after reperfusion, the levels of the PGs and TXB2 were virtually normal; at that time substantial recovery of neurologic motor functions were also observed. Eighteen hours after the ischemic insult most rabbits had minimal hopping function. This model is highly reproducible in producing a consistent functional outcome as observed in previous studies. The secondary increase in TXB2 at 18 hours after ischemia, especially in rabbits with poor functional status, again suggests an increased availability of AA, which may represent the possibility of a secondary ischemic event or membrane damage. However, no data are now available on tissue perfusion in this model. Systemic physiologic variables like blood gases, MAP, HR, and T do not appear to be involved in the secondary motor deterioration phenomenon. Even though HR was significantly increased during the early reperfusion phase, the increments were modest and values were in the normal range when motor deterioration developed. Although the increase in TXB2 at 18 hours is modest, its effects might be pronounced since the tissue at this time is already damaged and therefore might be more vulnerable to even small additional insults. It is tempting to speculate that the delayed deterioration might be at least partially due to damage produced by the secondary formation of TXA2, presumably by platelets and/or inflammatory cells such as macrophages and neutrophils. This possibility is supported by recent studies showing platelet and leukocyte accumulation in ischemic brain tissue. However, an alternative explanation for TXA2 release is a response to membrane damage where TXA2 may serve as an indicator of cellular injury.

Edema formation in ischemic tissue is a well established phenomenon. In the present study, increases in tissue water content in both gray and white matter were observed as early as 5 minutes after reperfusion. At 30 minutes of reperfusion, we found that edema continued to increase. However, by 4 hours, tissue water content was back to normal. An increase in edema between 4 and 24 hours in both gray and white matter correlated well with the secondary deterioration of neurologic function. Several studies suggest that PGs, particularly PGE2, may be involved in the development of edema after ischemic brain injury. However, in studies in which PG synthesis was blocked by indomethacin, no effect on edema formation after ischemia was seen. However, failure by indomethacin alone to block edema formation might be due to the persistent production of other proedematous eicosanoids through the lipxygenase pathway and especially the formation of leukotrienes which, together with other 5-lipoxygenase metabolites of AA, increase vascular permeability and promote tissue edema. This possibility is supported by recent reports showing elevated leukotriene levels during reperfusion after brain...
ischemia and the increase in 5-HETE (a 5-lipoxygenase metabolite) during reperfusion after spinal cord ischemia in rabbits.

During the 18–24 hour period, we observed an increase in the number of necrotic neurons, which may be responsible for the increased fluid accumulation due to osmotic differences between the blood and tissue. However, the increase in tissue water may also increase tissue pressure, resulting in a concomitant decrease in local microcirculatory blood flow. Interestingly, the number of necrotic neurons increased over time, from the intermediate to intermediate-dorsal to VH regions of the spinal cord. This agrees with studies in which normal spinal cord blood flow was reported to be highest in the intermediate gray region with progressively lower values in the intermediate-dorsal to the VH and may reflect the sensitivity of neurons in

![Figure 6](http://stroke.ahajournals.org/)

**Figure 6.** A. Tissue edema measured as specific gravity in different regions of the rabbit spinal cord subjected to 25 minutes of aortic occlusion. Tissue water content temporarily increased in ventral horn, dorsal white, and ventral white but returned to normal levels by 4 hours. At 18 hours, tissue water content was significantly increased in the ventral horn followed by significant increases in all regions by 24 hours after reperfusion. (p<0.05, **p<0.01, ANOVA followed by Dunnett's test). B. Composite graph of edema (Figure 6A) and neurologic score (Figure 1B) during the 24-hour reperfusion period. The pattern of tissue edema changes in each region of the spinal cord followed the pattern of neurologic changes. Neurologic score as median values.

![Figure 7](http://stroke.ahajournals.org/)

**Figure 7.** A. The major histopathologic changes after 25 minutes of aortic occlusion in rabbits were neuronal necrosis and vacuolation of the neuropil (edema formation) in the lumbar spinal cord. Lesions at 24 hours in the dorsal and ventral horns and intermediate gray matter. Hematoxylin and eosin stain, bar = 300 μm. B. Neuronal necrosis indicated by arrows. Micrograph of the intermediate gray matter after 24 hours of reperfusion. CC, central canal; hematoxylin and eosin stain, bar = 50 μm. C. Vacuolation of the neuropil indicated by arrows, necrotic neurons indicated by arrowheads. Micrograph of the ventral gray matter after 24 hours of reperfusion. Hematoxylin and eosin stain, bar = 50 μm.
these regions to blood flow changes. The histopathologic changes observed in this model during the first 24 hours after ischemia are reported here for the first time. Several rabbits were also followed to 7 days, and the histopathologic changes such as neuronal necrosis, edema, etc., were similar to those reported by DeGirolami and Zivin. In summary: This study describes a model with characteristics similar to the clinical condition termed "deteriorating stroke." The primary event in this model is the continuous deterioration of motor function during reperfusion after an initial ischemic insult. This deterioration is associated with increased tissue edema and increased formation of TxA. However, the relations of the increased TxA to tissue edema, histopathologic changes, and late functional deficits need further investigation.

Acknowledgments

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13. Rodrigues AM, Gerritsen ME: Prostaglandin release from isolated rabbit cerebral cortex microvessels. Comparison of 6-keto-PGF₁α and PGE₂ released from microvessels incubated in 100% O₂, room air and 95% N₂; 5% CO₂. Stroke 1984;15:717–722

Table 4. Neurologic and Histopathologic Scores Observed in Rabbit Spinal Cord After 25 Minutes of Ischemia

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<th>Time after reperfusion</th>
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Association between scores was highly significant by Spearman's rank correlation test ($r_s = 0.642, p < 0.01, n = 23$).

**Key Words** • prostaglandins • thromboxane • stroke • edema • rabbits
Deteriorating stroke model: histopathology, edema, and eicosanoid changes following spinal cord ischemia in rabbits.

T P Jacobs, E Shohami, W Baze, E Burgard, C Gunderson, J M Hallenbeck and G Feuerstein

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