Effects of Topical Administration of Y-39983, a Selective Rho-Associated Protein Kinase Inhibitor, on Ocular Tissues in Rabbits and Monkeys

Hideki Tokushige,1 Masaru Inatani,2 Shingo Nemoto,1 Hideyuki Sakaki,1 Koushirou Katayama,3 Masayoshi Uebata,3 and Hidenobu Tanibara2

PURPOSE. To elucidate the intraocular pressure (IOP)-lowering effects and associated characteristics of Y-39983, a selective Rho-associated coiled-coil-forming protein kinase (ROCK) inhibitor derived from Y-27632, in animal eyes.

METHODS. Y-39983 was compared with Y-27632 for selectivity of ROCK inhibition by biochemical assay. The IOP was monitored by pneumotonometer in albino rabbits and cynomolgus monkeys that were given topically administered Y-39983. The total outflow facility and uveoscleral outflow were measured by two-level constant-pressure perfusion and perfusion technique using fluorescein isothiocyanate-dextran, respectively, at 2 hours after topical administration of Y-39983 in albino rabbits. The ocular toxicologic effects of topical administration of Y-39983 were observed in albino rabbits and cynomolgus monkeys.

RESULTS. A biochemical assay showed that Y-39983 inhibited ROCK more potently than Y-27632. In rabbits, topical administration of Y-39983 significantly increased conventional outflow by 65.5%, followed by significant, dose-dependent reduction in IOP. Maximum IOP reduction was 13.2 ± 0.6 mm Hg (mean ± SE) at 0.1% Y-39983 in rabbits. In monkeys, at 3 hours after topical administration of 0.05% Y-39983, maximum reduction of IOP was 2.5 ± 0.8 mm Hg. No serious side effects were observed in ocular tissues except sporadic punctate subconjunctival hemorrhage during long-term topical administration of Y-39983 four times a day (at 2-hour intervals) in rabbits or monkeys. However, punctate subconjunctival hemorrhage was not observed with administration twice daily (at a 6-hour interval) or three times a day (at 5-hour intervals).

CONCLUSIONS. Y-39983 causes increased outflow facility followed by IOP reduction. Y-39983 ophthalmic solution may be a candidate drug for lowering of IOP, since it increases conventional outflow and produces relatively few side effects. (Invest Ophthalmol Vis Sci. 2007;48:3216–3222) DOI: 10.1167/iovs.05-1617

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Because the small GTPase Rho plays critical roles in signaling pathways that lead to formation of actin stress fibers and focal adhesions,1–6 it regulates various cellular behaviors including cytoskeletal rearrangement,5,6 cell morphology,7 cell motility,6 cytokinesis,9 and smooth muscle contraction.10,11 These effects of Rho are mediated by downstream Rho effectors such as Rho-associated coiled-coil-forming protein kinase (ROCK) and mDia. The GTP-bound forms of Rho activate these Rho effectors that control the actin cytoskeleton, resulting in changes in morphology and adhesion of fibroblasts and epithelial cells.12–16 Inhibitors of ROCK have been developed because of their potential for use in treating metastasis and axon injury. Among these inhibitors, Y-27632 is the first identified specific inhibitor of the ROCK family of protein kinases.17 In our previous studies, Y-27632 was found to lower intraocular pressure (IOP) in rabbit eyes.18,19 Our previous studies also revealed that Y-27632 altered the contractility of the trabecular meshwork (TM) cells and ciliary muscle (CM). Recently, alteration in contractility, focal adhesion, and stress fiber formation in Schlemm’s canal (SC) cells, TM cells, and CM have been proposed to lower IOP.18–30 ROCK inhibitors are thus considered candidates for novel IOP-lowering antiglaucoma drugs.18,19,25,26

In addition, it has been reported that other protein kinase inhibitors such as H-7 and HA-1077 have ROCK inhibitory activity, though their specificity for ROCK is less than that of Y-27632.17 H-7 and HA-1077 also reduce IOP by increasing conventional outflow by altering the contractility of TM and the cellular behavior of TM cells.27–30 These inhibitors may also have potential for development as antiglaucoma drugs to lower IOP.

Thus, inhibition of the Rho-ROCK signaling pathway is a new target for glaucoma treatment. In the present study, a novel selective ROCK inhibitor, Y-39983, inhibited Rho-ROCK signaling more potently than Y-27632, and topical administration of it facilitated aqueous conventional outflow, resulting in a lowering of IOP. We also examined the toxicologic effects of topical administration to evaluate the possibility of clinical use of Y-39983.

MATERIALS AND METHODS

Animals

In pharmacological studies (measurements of IOP and aqueous outflow), adult male Japanese white (albino) rabbits weighing 2.0 to 2.8 kg and adult male cynomolgus monkeys (Macaca fascicularis) weighing 6.0 to 8.9 kg were used. In this experiment, adult cynomolgus monkeys were trained for measurement of IOP in conscious condition (without systemic anesthesia). In toxicologic studies, adult male Japanese white rabbits weighing 1.8 to 2.7 kg and adult male and female cynomolgus monkeys weighing 2.2 to 3.5 kg were used. All studies were conducted in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research.

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For IOP measurements in rabbits and monkeys, the eyes were anesthetized by topical instillation of 0.04% and 0.4% oxybuprocaine hydrochloride, respectively.

**Chemicals and Drug Preparation**

Y-27632 (molecular weight [MW] 338.3) and Y-39983 (MW 316.8) were synthesized by Mitsubishi Pharma Corp. (Osaka, Japan). The structures of Y-27632 and Y-39983 are shown in Figure 1. Staurosporine, a nonspecific protein kinase inhibitor, was purchased from Wako Pure Chemical (Osaka, Japan). In the topical administration experiments, Y-39983 was used as an ophthalmic solution containing preservative for clinical use. In addition, 0.05% latanoprost (Xalatan; Pfizer, Tokyo, Japan) was used as a comparator in examination of IOP-lowering effects.

**Measurement of Inhibition of ROCK, Protein Kinase C, and Calmodulin-Dependent Protein Kinase II**

Recombinant ROCK (ROK α/ROK II) and purified protein kinase C (PKC; mixture of α, β, γ isoforms) were purchased from Upstate Biotechnology (Lake Placid, NY). Recombinant calmodulin-dependent protein kinase II (CaMKII) was purchased from Daiichi Pure Chemical (Tokyo, Japan). ROCK (0.2 U/mL) was incubated with 1 μM [γ-32P] ATP and 10 μg/mL histone as substrates in the absence or presence of various concentrations of Y-27632, Y-39983, or staurosporine at room temperature for 20 minutes in 20 mM MOPS buffer (3-[N-morpholino]propanesulfonic acid) buffer (pH 7.2) containing 1 mg/mL bovine serum albumin (BSA), 5 mM dithiothreitol [DTT], 10 mM β-glycerophosphate, 50 μM Na2VO4, and 10 mM MgCl2 in a total volume of 100 μL. PKC (10 ng/mL) was incubated with 1 μM [γ-32P] ATP and 20 μg/mL PKC substrate (Peptide Institute, Osaka, Japan) in the absence or presence of various concentrations of Y-27632, Y-39983, or staurosporine at room temperature for 30 minutes in 20 mM MOPS buffer (pH 7.5) containing 0.1 mg/mL BSA, 10 mM DTT, 10 mM β-glycerophosphate, 50 μM Na2VO4, 2 mM CaCl2, 20 μg/mL phosphatidylserine, and 10 mM MgCl2 in a total volume of 100 μL. CaMKII (125 U/mL) was incubated with 1 μM [γ-32P] ATP, 10 μM calmodulin, and 20 μM CaMKII substrate (Daiichi Pure Chemical), in the absence or presence of various concentrations of Y-27632, Y-39983, or staurosporine at room temperature for 30 minutes in 20 mM MOPS buffer (pH 7.5) containing 0.1 mg/mL BSA, 0.5 mM DTT, 0.1 mM β-glycerophosphate, 50 μM Na2VO4, 1 mM CaCl2, and 5 mM MgCl2 in a total volume of 100 μL. Incubation was terminated by the addition of 100 μL of 0.7% phosphoric acid. A 160 μL portion of the mixture was transferred to Multiscreen-PH plate (Millipore, MA). A positively charged phosphocellulose filter absorbed the substrate that bound32P (Multiscreen-Vacuum manifold; Millipore). The filter was washed with 300 μL of 0.5% phosphoric acid and then twice with purified water and then dried. The radioactivity of the dried filter was measured with a liquid scintillation counter (IS6500; Beckman Instruments, Fullerton, CA). Results are presented as 50% inhibitory activity and 95% confidence intervals (CI).

**IOP Measurements**

Pneumotonometers (Alcon, Fort Worth, TX, or Medtronic Solan, Jacksonville, FL) were used to monitor IOP. In the experiments involving single topical administration in rabbits and monkeys, 50 μL of Y-39983 at concentrations of 0.003% to 0.1% (0.1% in rabbits only) was topically administered to one eye. In addition, 0.005% latanoprost was topically administered as a comparator to one eye in monkeys. Saline was topically administered to the contralateral eyes in both species. IOPs were measured before topical administration and at 1, 2, 3, 5, 7, 9, and 12 hours (12 hours in monkeys only) after administration. In the experiments on repeated topical administration using rabbits, 50 μL of 0.03% Y-39983 was topically administered to one eye four times a day (QID; 10:00, 13:00, 16:00, and 19:00, at 3-hour intervals) for 28 days. The contralateral eyes were not treated. IOPs were measured at maximum reduction (2 hours after topical administration in the morning) at 7, 14, 21, and 28 days after administration. The vehicle of Y-39983 was used as the control. IOPs were calculated from the difference between results for Y-39983 or its vehicle-treated eyes and the contralateral saline-treated or nontreated eyes at each time point.

**Measurement of Total Outflow Facility and Uveoscleral Outflow**

Total outflow facility was determined by two-level constant pressure perfusion (25 and 35 mm Hg) at 2 hours after topical administration of 50 μL of 0.05% Y-39983 in one eye and its vehicle in the contralateral eye, according to the method of Bárány. Briefly, the anterior chambers of rabbits anesthetized with 40% urethane were perfused with mock aqueous humor (Opeguard MA; Senju Pharmaceutical, Osaka, Japan) with a constant pressure of either 25 or 35 mm Hg, which was alternately applied for 10-minute intervals. During each 10-minute period, fluid flow was measured for 8 minutes, beginning 2 minutes after pressure change.

Uveoscleral outflow was determined with a perfusion technique using fluorescein isothiocyanate-dextran (FITC-dextran, mean MW, 71,200; Sigma-Aldrich, St. Louis, MO),32,33 at 2 hours after topical administration of 50 μL of 0.05% Y-39983 in one eye and its vehicle in the contralateral eye. Rabbits were anesthetized with 40% urethane, and two 23-gauge needles connected to a pair of syringes were inserted into the anterior chamber of each eye of each rabbit. The pair of syringes was controlled by an infusion-withdrawal pump (Model 55-1382; Harvard Apparatus, S. Natick, MA), and the infusion syringe was filled with 10 M FITC-dextran. One milliliter of the FITC-dextran solution was washed through the anterior chamber from the syringes at a rate of 0.5 mL/min. The IOP level was then set to 20 mm Hg. The FITC-dextran solution was perfused continuously through the anterior chamber at a rate of 10 μL/min for 30 minutes. The anterior chamber was washed with 2 mL of PBS at a rate of 0.5 mL/min. Each eye was then enucleated and dissected into the following sample groups: anterior uvea, anterior sclera, posterior sclera plus posterior uvea, and posterior segment fluid plus vitreous. All samples were homogenized and centrifuged, and then each volume was measured. The supernatant was measured to determine FITC-dextran concentration using a fluorophotometer. Uveoscleral outflow (Fu) was calculated as follows:

\[
Fu (\muL/min) = \frac{\sum (a \times b)(ng)}{C(ng/\muL) \times T(min)}
\]

where \(a\) is the volume of each sample, \(b\) is the concentration of FITC-dextran in each sample, \(C\) is the concentration of FITC-dextran in the perfusion fluid (10 M = 7120 ng/mL); and \(T\) is the time of perfusion (30 minutes).

**Ocular Toxicology**

Ocular toxicologic properties of Y-39983 were evaluated in rabbits and monkeys. In the QID study, performed to test severe conditions, 100 μL of Y-39983 (0.003%–0.03%) or saline as a control was topically administered to both eyes of the rabbits at 2-hour intervals for 4 weeks (\(n = 5\)). In addition, 50 μL of Y-39983 (0.003%–0.05%) or its vehicle was topically administered four times a day at 2-hour intervals for 26
weeks (n = 8). In slit lamp examinations, the cornea (epithelial defects revealed by fluorescein biostaining, opacity, and neovascularization), conjunctiva (hyperemia, swelling), anterior chamber (flare), and iris (hyperemia, swelling) were observed. The lens, vitreous, and retina were observed in eyes under mydriasis, with a slit lamp and binocular indirect ophthalmoscope. Tear quantity was measured by phenol red thread (Zonequick; Menicon, Nagoya, Japan). The electroretinogram (ERG) was measured to evaluate retinal safety. In darkness and under mydriasis with systemic anesthetization, a contact lens-type electrode was fitted to the eye. Results of light stimulation and the ERG were recorded using a veterinary ERG system. Amplitudes of the a- and b-waves and the peak latency were determined. In addition, histologic examination was performed by the usual method after the last observation. The tissues observed were the eye including the palpebral and conjunctiva, and optic nerve, lacrimal glands, internal organs including the liver, gallbladder, kidneys, spleen, heart, aorta, gullet, stomach, intestines, lungs, and bronchial tube, sex organs, brain, bone, muscle, skin, and other tissues.

In addition, to investigate the safety of Y-39983 at various frequencies of administration, the drug was administered two and three times a day (BID and TID) to rabbits and monkeys. In rabbits in the BID study, 0.05% or 0.1% Y-39983 or saline was topically administered to both eyes twice daily (with a 6-hour interval) for 4 weeks (n = 3). In rabbits in the TID study, 0.1% Y-39983 or saline was topically administered three times a day at 5-hour intervals for 2 weeks (n = 5). In monkeys in the BID study, 0.05%, 0.1%, or 0.2% Y-39983 or saline was topically administered twice daily at a 6-hour interval for 4 weeks (n = 3). Ocular tissues were observed in the same fashion as for administration four times a day.

**Effects on Cultured Human Umbilical Venous Endothelial Cells**

Human umbilical venous endothelial cells (HUVECs) were purchased from Dainippon Pharmaceutical (Osaka, Japan). HUVECs were cultured in CS-C medium (Dainippon Pharmaceutical) and maintained in a 95% air-5% CO2 atmosphere at 37°C and passaged using the trypsin-EDTA method. HUVECs were seeded into 24-well plates. After seeding, HUVECs were incubated in medium containing 1 μM Y-39983 for 15 or 30 minutes and observed by phase-contrast microscopy. Medium was then removed, and HUVECs were incubated in medium without Y-39983 for 1 hour to evaluate recovery from the morphologic changes induced by Y-39983.

**RESULTS**

**Selective Inhibitory Effect of Y-39983 on ROCK Activity**

Results are summarized in Table 1. The 50% inhibitory concentration (IC50) of Y-27632 for ROCK (0.11 μM; 95% CI, 0.074–0.17 μM), was 30.6 times that of Y-39983 (0.0036 μM; 95% CI, 0.0025–0.0051 μM). In contrast, in the examination of inhibition of PKC and CaMKII, the IC50s of Y-27632 and Y-39983 for PKC were 9.0 μM (95% CI, 7.1–11 μM) and 0.42 μM (95% CI, 0.36–0.49 μM), respectively, whereas the IC50s of Y-27632 and Y-39983 for CaMKII were 26 μM (95% CI, 21–32 μM) and 0.81 μM (95% CI, 0.67–0.97 μM), respectively. The IC50s of Y-27632 and Y-39983 for PKC were 82 and 117 times those for ROCK, respectively, whereas the IC50s of Y-27632 and Y-39983 for CaMKII were 236 and 225 times those for ROCK, respectively. In addition, the same experiments were performed as controls using staurosporine, a nonspecific protein kinase inhibitor. Staurosporine exhibited the same inhibitory effects on all three kinases—ROCK, PKC, and CaMKII—as shown in Table 1. These findings indicate that Y-39983 more potently inhibits ROCK than Y-27632 and has the same selectivity for ROCK as Y-27632. In addition, Y-39983 was more selective for ROCK than staurosporine.

### Table 1. Selective Inhibitory Effect of Y-39983 on ROCK

<table>
<thead>
<tr>
<th>Compounds</th>
<th>ROCK (μM)</th>
<th>PKC (μM)</th>
<th>CaMKII (μM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-39983</td>
<td>0.0036</td>
<td>(0.0025–0.0051)</td>
<td>0.81 (0.67–0.97)</td>
</tr>
<tr>
<td>Y-27632</td>
<td>0.11</td>
<td>(0.074–0.17)</td>
<td>26 (21–32)</td>
</tr>
<tr>
<td>Staurosporine</td>
<td>0.0011</td>
<td>(0.00078–0.0015)</td>
<td>0.00036 (0.00003–0.00040)</td>
</tr>
</tbody>
</table>

In parentheses, 95% confidence interval; in brackets, comparison with the IC50 of ROCK.

**IOP Measurements in Rabbit Eyes**

In rabbits, Y-39983 lowered IOP in a dose-dependent fashion, as shown in Figure 2A. Statistically significant IOP-lowering effects were found at concentrations of Y-39983 equal to or higher than 0.01% at 2 hours after topical administration. IOP reduction was at maximum between 2 and 3 hours after administration of 0.05% Y-39983, 9.6 mm Hg during the 28-day period, demonstrating that maintenance over 28 days. Mean reduction of IOP was between 7.0 and 9.6 mm Hg. Figure 3 shows the time course of changes in peak IOP reduction. In monkeys, Y-39983 dose dependently lowered IOP, as shown in Figure 4A. Compared with vehicle-treated eyes, 0.05% Y-39983-treated eyes in particular exhibited significant reductions in IOP between 2 and 7 hours after topical administration (P < 0.05, the Dunnett’s test, one-sided). The reduction of IOP was at maximum 3 hours after administration of 0.05% Y-39983. The reductions of IOP (mean ± SE) at 2, 3, 5, and 7 hours after administration of 0.05% Y-39983 were 1.9 ± 0.3, 2.5 ± 0.4, 1.7 ± 0.3, and 0.8 ± 0.2 mm Hg, respectively. Maximum IOP reduction (mean ± SE) was 0.4 ± 0.1, 0.4 ± 0.2, 1.4 ± 0.3 (P < 0.05 vs. vehicle-treated eyes, Williams’ test, one-sided).
and 2.5 ± 0.8 mm Hg (P < 0.05) at 0.003%, 0.01%, 0.03%, and 0.05% Y-39983, respectively (Fig. 4B). Statistically significant reduction of IOP was obtained at concentrations of Y-39983 equal to or greater than 0.05%. Administration of 0.005% latanoprost lowered IOP by 2.5 ± 0.2 mm Hg (P < 0.001 vs. vehicle-treated eyes; t-test, one-sided), demonstrating that the IOP-lowering effect of 0.05% Y-39983 was similar to that of 0.005% latanoprost.

**Measurements of Total Outflow Facility and Uveoscleral Outflow**

Outflow facility was measured 2 hours after topical administration of 0.05% Y-39983, when maximum IOP reduction was observed. As summarized in Table 2, outflow facility (mean ± SE) in eyes treated with Y-39983 (0.168 ± 0.018 μL/min/mm Hg) was approximately 1.7 times (+65.5%) that in the contralateral, vehicle-treated eyes (0.111 ± 0.014 μL/min per mm Hg). This difference was significant (P < 0.001, paired t-test, one-sided). In contrast, there were no significant differences in uveoscleral outflow between eyes treated with Y-39983 and those treated with vehicle.

**Ocular Toxicologic Effects of Topical Administration of Y-39983**

Ocular toxicologic properties were evaluated for long-term topical administration of Y-39983. In the QID study, rabbit eyes were treated with 0.003% to 0.03% Y-39983 four times a day (at 2-hour intervals) for 4 weeks, and monkey eyes with 0.003% to 0.05% Y-39983 at the same dosage for 26 weeks. In neither species were significant abnormalities of the corneal surface, anterior chamber, lens, vitreous, or retina observed on slit lamp examination, nor were significant findings of toxicity detected on histologic examination. ERG analysis revealed no abnormalities in eyes treated with Y-39983 of either species. At week 4, thread-wetting values (mean millimeters ± SE) for rabbits determined by the phenol red thread method were 29.4 ± 1.7, 29.4 ± 0.9, 28.8 ± 1.0, and 29.0 ± 1.1 mm with saline, 0.003%, 0.01%, and 0.03% Y-39983, respectively. At week 25, the thread-wetting values in monkeys were 30.0 ± 1.0, 28.5 ± 1.0, 31.0 ± 0.7, 28.9 ± 1.1, and 29.1 ± 0.8 mm with vehicle, 0.003%, 0.01%, 0.03%, and 0.05% Y-39983, respectively. There were no differences in thread-wetting values between the groups of rabbits and monkeys. However, conjunctival hyperemia and punctate subconjunctival hemorrhage were observed in eyes with topical administration of Y-39983 in rabbits (Fig. 5A) and monkeys (Fig. 5B), and punctate subconjunctival hemorrhage was sporadic during the administration period in both species. In the QID study, punctate subconjunctival hemorrhages were observed in four of five rabbits receiving 0.03% Y-39983 and in two of eight monkeys receiving 0.05% Y-39983. The hemorrhages resolved during the administration period. However, in the BID and TID studies,
In the present study, topical administration of a selective in-versible and had nearly recovered by 1 hour after removal of cultured HUVECs after the addition of Y-39983. In medium junctival hemorrhages, we examined morphologic changes in elucidate the mechanisms responsible for the punctate subcon- was observed in eyes treated with Y-39983 in both species. To further investigating effect of Y-39983 in monkey eyes suggests the possibility of clinical use of this compound.

In this study, we examined the IOP-lowering effects of Y-39983 in rabbits and monkeys. With 0.05% Y-39983, maximum reductions of IOP were 12.1 ± 1.5 (mean ± SE) and 2.5 ± 0.2 mm Hg in rabbits and monkeys, respectively, showing that the magnitude of effect of Y-39983 in monkeys was much less than that in rabbits. This difference between species may be explained by the difference in baseline IOPs, which were 22.0 ± 0.6 and 17.5 ± 0.2 mm Hg in rabbits and monkeys, respectively. In fact, it has been reported that the IOP-lowering effects of H-7 and prostaglandin analogues in monkeys, which have low baseline IOPs, are weaker than that in rabbits, which have high baseline IOPs.30,37 In a preliminary significantly reduced IOP in rabbit and monkey eyes. Several clinical investigations have revealed that elevated IOP is a major factor that causes glaucomatous optic neuropathy.34–36 Because they potently lower IOP in mammalian eyes, ROCK inhibitors have been considered potential drugs for the treatment of glaucoma.18,19 In this study, we examined the efficacy and safety of Y-39983 for potential clinical application.

Although our previous study revealed significant IOP-low-ering effects of Y-27632 in animal eyes,16,17 for potential clinical use, this compound has the disadvantage of poor stability in solution (data not shown). A series of modifications of molecular structure was therefore conducted to develop a more suitable form and more potent ROCK inhibitory activity for clinical use. Among the forms obtained, Y-39983 exhibits potent inhibition of ROCK activity and has acceptable stability, even in solution. Furthermore, we found that the ratio of IC50 for inhibition of ROCK/PKC for Y-39983 was 117 while that for Y-27632 was 82, suggesting that Y-39983 has the same specificity for ROCK as Y-27632. Also, the inhibition of ROCK by Y-39983 was 30 times that by Y-27632. These in vitro findings suggest that Y-39983 is a more useful candidate for an antiglaucoma drug than Y-27632. In our previous study,18 Y-27632 at concentrations of 0.34% to 3.4% reduced IOP by 7 to 12 mm Hg in rabbit eyes under the same conditions of administration as in this study. Reduction of IOP (ΔIOP ≥ 10 mm Hg) was observed with a lower dose of Y-39983 (0.03%–0.1%). In addi- tion, the degree of reduction of IOP (maximum ΔIOP = 5.3 mm Hg) obtained with Y-27632, as determined in a previous study,15 was observed with 0.01% Y-39983 (peak ΔIOP = 6.6 mm Hg). These findings together suggest that the reduction of IOP by Y-27632 is approximately 10-fold higher than that by Y-27632. These findings appear to agree with our in vitro result that the ROCK inhibitory activity of Y-39983 is 30 times that of Y-27632.

In considering clinical application of Y-39983, the next important question is whether Y-39983 is also effective in lowering IOP in primate eyes, since primate eyes have a mo-dality of aqueous outflow different from that of lower mamma-lian eyes. The present study revealed that, even in monkey eyes, 0.05% Y-39983 induces significant IOP reduction almost equal to that obtained with 0.005% latanoprost. The IOP-lowing effect of Y-39983 in monkey eyes suggests the possibility of clinical use of this compound.

In this study, we examined the IOP-lowering effects of Y-39983 in rabbits and monkeys. With 0.05% Y-39983, maximum reductions of IOP were 12.1 ± 1.5 (mean ± SE) and 2.5 ± 0.2 mm Hg in rabbits and monkeys, respectively, showing that the magnitude of effect of Y-39983 in monkeys was much less than that in rabbits. This difference between species may be explained by the difference in baseline IOPs, which were 22.0 ± 0.6 and 17.5 ± 0.2 mm Hg in rabbits and monkeys, respectively. In fact, it has been reported that the IOP-lowering effects of H-7 and prostaglandin analogues in monkeys, which have low baseline IOPs, are weaker than that in rabbits, which have high baseline IOPs.30,37 In a preliminary

![Graph](image_url)

**FIGURE 4.** Effects of topical administration of Y-39983 on IOP in monkey eyes. Y-39983 or its vehicle was topically administered to one eye in monkeys. The contralateral eyes were treated with the same volume of saline (n = 5). (A) Time course of changes in IOP. (C) vehicle; (○) 0.003%; (●) 0.01%; (▲) 0.05%; and (●) 0.05% of Y-39983. (D) 0.005% latanoprost. IOPs were calculated as the difference between the value in Y-39983 or vehicle-treated eyes and contralateral saline-treated eyes at each time point. Data are the mean mm Hg ± SE. The significance of findings was evaluated by the Dunnett’s test (one-sided); **p < 0.05 and ***p < 0.01, compared with the vehicle group at each time point. (B) Maximum IOP reduction. Data are the mean mm Hg ± SE. The significance of findings was evaluated by the Williams’ test (one-sided) *P < 0.05, and by t test (one-sided) ###P < 0.001, compared with the vehicle group. Baseline IOPs were 17.8 ± 0.2, 17.9 ± 0.2, 17.8 ± 0.4, 17.3 ± 0.2, and 17.5 ± 0.2 mm Hg (mean ± SE) with vehicle, 0.003%, 0.01%, 0.05%, and 0.05% Y-39983, respectively.

punctate subconjunctival hemorrhages were not observed in eyes treated with Y-39983, although conjunctival hyperemia was observed in eyes treated with Y-39983 in both species. To elucidate the mechanisms responsible for the punctate subcon- junctival hemorrhages, we examined morphologic changes in cultured HUVECs after the addition of Y-39983. In medium containing 1 μM Y-39983, HUVECs exhibited contraction (Figs. 6A–C). The morphologic changes in HUVECs were revers-ible and had nearly recovered by 1 hour after removal of Y-39983 (Fig. 6D).

**DISCUSSION**

In the present study, topical administration of a selective in-hibitor of the ROCK/ROK family of protein kinases, Y-39983,
pharmacokinetics study after topical administration of Y-39983, the disappearance of Y-39983 in tears of monkeys was faster than that in rabbits, and this difference in pharmacokinetics may be due to differences in frequency of blinking in these species. This difference in pharmacokinetics may also have resulted in the difference in IOP-lowering effects in rabbits and monkeys in this study.

There are two routes of aqueous humor outflow: that via the conventional (trabecular) and that via the unconventional (uveoscleral) pathway. In primate and human eyes, conventional outflow is considered the main route and is believed to be regulated by the cellular behavior and contractility of TM cells. Our previous study showed that Y-27632 increased conventional outflow by altering the contractility of TM cells. In addition, Y-27632 has been shown to increase conventional outflow by inducing cellular relaxation and loss of cell–substrate adhesion in the TM and in SC cells. The IOP-lowering mechanism of H-7, a broad-spectrum inhibitor of serine-threonine kinases including ROCK, has been investigated. H-7 also increases conventional outflow by altering the shape, actin cytoskeleton, and cell–cell adhesion of TM and SC cells, as Y-27632. Thus, alterations of TM and SC cells affect conventional outflow, and compounds causing cytoskeletal change in TM and SC cells may potentially be useful as antiglaucoma drugs.

In our toxicologic study, no serious side effects were observed in ocular tissues of rabbits and monkeys except sporadic punctate subconjunctival hemorrhage. This type of hemorrhage was observed after frequent administration of Y-39983 (four times a day at 2-hour intervals). The side effects may be explained by impairment of barrier function or morphologic changes in vascular endothelial cells, as shown in the experiments using HUVECs. The morphologic changes in HUVECs observed after the addition of Y-39983 suggest the possibility of impairment of barrier function in vascular endothelial cells in the retina, since the Rho-ROCK signaling pathway is considered ubiquitous. However, our animal experiments did not reveal detectable hemorrhages in the iris-ciliary body or retina-choroid, suggesting that the concentration at which lowering of IOP is elicited may not be high enough to induce hemorrhage in the ocular fundus. Also, subconjunctival hemorrhage, which was encountered with frequent administration (four times a day), was not observed with administration two or three times a day. It is possible that no side effects will be induced in the conjunctiva with clinical usage of Y-39983, if excessively frequent instillation is avoided.

In summary, the present study showed that Y-39983, a selective and potent ROCK inhibitor, reduced IOP and increased aqueous outflow. Selective inhibition of the Rho/ROCK signaling pathway may be a useful new strategy for the treatment of glaucoma, and Y-39983 ophthalmic solution may be a candidate drug since it lowers IOP by increasing aqueous outflow and produces fewer side effects.

References


