Effects of Sodium Lactate on Isolated Rabbit Corneas

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Corneal stromal lactate accumulation may result from epithelial hypoxia and contact lens wear, but the possible corneal toxicity of lactate has not been reported. Isolated superfused whole rabbit corneas were examined for thickness changes during exposure to neutral sodium lactate (NaL) or excess sodium chloride (NaCl) in Krebs-bicarbonate Ringer's solution for a 3-hr period. Placed in the tears side bath, 5 mM NaL significantly thinned corneas (swelling rates of $1 \pm 1 \mu m/hr$ in Ringer's controls vs $-11 \pm 1 \mu m/hr$ in lactate-treated corneas; mean $\pm$ SD). Excesses of 5 mM NaCl had essentially identical effects ($0 \pm 1 \mu m/hr$ in controls vs $-13 \pm 3 \mu m/hr$ in experimentals). When placed on the aqueous side of normal-thickness corneas, neither 20 mM NaL nor 20 mM excess NaCl affected corneal thickness, but both solutions stimulated endothelium-mediated deswelling in preswollen de-epithelialized corneas. When “loaded” into the stroma of deepithelialized corneas, Ringer containing 20 mM lactate caused more swelling than Ringer’s alone (491 $\pm$ 18 $\mu m$ in controls vs 558 $\pm$ 20 $\mu m$ in loaded corneas; mean $\pm$ SEM). A similar swelling occurred when 20 mM excess NaCl was loaded into the stroma (483 $\pm$ 15 vs 565 $\pm$ 20 $\mu m$ in controls and loaded corneas, respectively), due to fluid uptake into the hypertonic stroma across the endothelium from the aqueous side (Ringer's) bath. Corneas both loaded and superfused with either NaL or excess NaCl swelled and subsequently deswelled similar to controls swollen and superfused in Ringer’s. These experiments demonstrate that like NaCl, NaL up to 20 mM appears to be nontoxic to the cornea, but can osmotically affect corneal thickness, which can acutely account for hypoxic corneal edema. Invest Ophthalmol Vis Sci 31:942–947, 1990

Materials and Methods

Male and female New Zealand White rabbits (2–3 kg) were sacrificed with a pentobarbital overdose via the marginal ear vein, and the corneas were mounted for specular microscopy in isolated superfused rabbit corneas. To determine the acute effects of lactate from the tears, aqueous, and stroma, these studies examined thickness changes by means of specular microscopy in isolated superfused rabbit corneas.

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was performed on each bathing solution with a Precision Systems Osmette A Osmometer, and all solutions had an osmolality of 300 ± 5 mOsm/kg before sodium lactate (NaL) or NaCl addition. Addition of 5 mM NaCl or NaL increased the osmolality to 310 ± 2 mOsm/Kg; 20 mM NaCl or NaL increased the osmolality to 340 ± 2 mOsm/Kg. All bathing solutions were made weekly and kept refrigerated, and all added agents (NaL, excess NaCl, adenosine, or glutathione) were added on the day of use. Reagents were obtained from Fisher Scientific (St. Louis, MO) except for adenosine, glutathione, and lactic acid, which were obtained from Sigma (St. Louis, MO). Lactic acid was converted to a 2 M NaL solution by equimolar titration with NaOH, and was kept frozen for no longer than 5 weeks.

**Normal-Thickness Corneas**

After a 1.5-hr equilibration period in the Ringer's solution, corneal thickness was monitored for a 3-hr experimental period. At the beginning of the 3-hr period (zero time), control and experimental corneas typically differed in thickness by less than 10 μm. If the difference exceeded 30 μm, the pair was rejected, based on apparent differences in initial corneal swelling pressure. At zero time, Ringer's containing NaL or excess NaCl was placed on the experimental corneas in either the tears side or aqueous side bath, and the paired control cornea was bathed in normal Ringer's. The thickness of each cornea was measured in duplicate at zero time and every 30 min (a total of 14 observations for each cornea). For each group of five to eight corneas, least squares linear regression analysis was conducted to determine the group swelling rate and its standard deviation. Group swelling rates were compared by analysis of covariance at the P < 0.05 level of significance as described by Hull et al.18

**Preswollen Corneas**

Corneas were deepithelialized with a Gill corneal knife and swollen with Ringer's on the denuded surface. After a thickness of approximately 560–580 μm was reached (approximately 1 hr), the solution was removed and blotted away from the stromal surface, and was replaced with silicone oil (Dow-Corning 360 Medical Fluid, 20 centistokes) to prevent further fluid exchange. After a 30–45-min equilibration under the oil, thickness was monitored for a 3-hr experimental period. This enabled an examination of deturgescence in the presence of NaL or excess NaCl in the aqueous bath.

**Lactate-“Loaded” Corneas**

Corneas were deepithelialized (See Preswollen Corneas, above) and exposed to Ringer's (controls) or Ringer's containing 20 mM NaL or excess NaCl (experimentals) to “load” the stroma with either Ringer's or Ringer's made hypertonic with NaL or NaCl. This enabled an examination of their effects on thickness and endothelium-mediated deturgescence. In one type of loading experiment, the aqueous bath contained Ringer's without NaL or excess NaCl. In a second protocol, the aqueous bath contained NaL or NaCl Ringer's identical to that loaded into the stroma. Thus, the second loading experiments were designed to minimize lactate gradients across the endothelium during deturgescence.

**Lactate Assay**

The corneas loaded with lactate by the first protocol were assayed for their concentration as described...
by Klyce, immediately after loading and measurement of thickness, or after 1.5 hr of deswelling. Lactate was assayed by the method of Bergmeyer using the Sigma lactate assay kit (Sigma catalog no. 826 UV), which utilizes beef heart lactate dehydrogenase to convert lactate to pyruvate. Pyruvate is trapped as a hydrazone to enable quantitative conversion of NADH to NAD, which is measured spectrophotometrically at 340 nm.

**Results**

**Effects of Lactate in the Aqueous Bath**

When placed on the aqueous side, Ringer's containing 20 mM NaL had no significant effect on corneal thickness or swelling rates compared to normal Ringer's (Fig. 1), and a similar finding was observed with 20 mM excess NaCl (Fig. 2). In addition, 20 mM NaL or excess NaCl apparently were not toxic to endothelium-mediated deturgescence in preswollen deepithelialized corneas (Figs. 3, 4); both agents stimulated deturgescence.

**Effects of Stromal Lactate in Ringer-Bathed Corneas**

When 20 mM NaL was loaded into deepithelialized corneas over a 45-min period, corneas swelled more than corneas swollen in Ringer's alone (491 ± 18 μm in controls vs 558 ± 20 μm in experiments; \( P < 0.01 \); Fig. 5). A similar finding was observed with NaCl-loaded corneas (483 ± 15 vs 565 ± 20 μm; \( P < 0.01 \); Fig. 6). Upon application of silicone oil to the bare stromal surface, the loaded corneas thinned faster than did Ringer's preswollen tissues. A comparison of loaded corneas at 1.5 hr with controls at zero time demonstrated that their thickness and deswelling rates were identical. The lactate concentration in the lactate-loaded stroma was higher than in Ringer's swollen controls at zero time, but not at 1.5 hr (Fig. 7).

**Effects of Stromal Lactate in Lactate-Bathed Corneas**

When both loaded and bathed with 20 mM NaL or excess NaCl, deepithelialized corneas swelled to simi-
Fig. 7. Lactate concentrations measured in lactate-loaded, Ringer’s-superfused stroma-endothelial tissues immediately after loading, or 1.5 hr after removal of the 20 mM lactate Ringer’s from the stromal surface. Groups bearing identical superscripts are significantly different from each other (P < 0.05; analysis of variance and Bonferroni t-test).

Fig. 8. When loaded and bathed with 20 mM excess NaCl, corneas deswelled at rates similar to controls swollen and bathed in Ringer’s (n = 5).

Fig. 9. When loaded and bathed with 20 mM excess NaCl, corneas deswelled at rates similar to controls swollen and bathed in Ringer’s (n = 5).

Effect of Lactate in the Tears Bath

On the tears side, 5 mM NaL or 5 mM excess NaCI thinned corneas, compared to Ringer’s bathed controls (Figs. 10, 11). Because tears-side concentrations of lactate are not elevated during corneal hypoxia, higher concentrations were not examined.

Discussion

This study demonstrates that 5 and 20 mM NaL is similar in all respects to equamilar excesses of NaCl. The immediate changes within 30 min of exposure to hypertonic solutions were not examined, but have been addressed elsewhere. From the aqueous side, neither agent had significant effects on the thickness of normal corneas (Figs. 1, 2), an observation which contrasted with the findings of Mishima and Hedbys. Their study clearly demonstrated the osmotic effects of 10–40 mM glucose on corneal thickness, and Wilson et al demonstrated similar effects with 1.25% NaCl. Those investigators had used preparations bathed on one side with silicone oil, however, preventing stromal-to-tears water and solute equilibration. The corneas used here were bathed with Ringer solution on both surfaces, constituting a multicompartment system which involves fluid and solute equilibration among the stroma and tears and aqueous sides, as addressed by Klyce and Russell. In preswollen corneas with silicone oil on their deepithelialized surface, 20 mM NaL or excess NaCI did significantly deswell corneas (Figs. 3, 4). The data suggests that lactate has no acutely deleterious effect on endothelium-mediated deturgescence.

Lactate-loaded corneas bathed in Ringer’s (Fig. 5), contained more lactate (Fig. 8) and swelled more than Ringer’s-loaded controls. Some lactate was lost...
by 1.5 hr (Fig. 7), so that controls and experimental
were not significantly different. Corneas loaded with
excess NaCl caused a similar initial swelling (Fig. 6),
indicating that lactate-induced edema is osmotic in
nature, as suggested by Klyce.4 The thicker, NaL-
or NaCl-loaded corneas deswelled faster than controls,
probably because of their lower stromal swelling
pressure. To determine whether swelling in the
loaded corneas resulted from toxicity gradients across
the endothelium, the second loading protocol was
used. Where NaL (Fig. 8) or excess NaCl (Fig. 9) also
bathed the aqueous side of loaded corneas, the cor-
neas swelled and deswelled identically to Ringer’s-bathed controls. This demonstrates that swelling
with the first loading protocol results from osmotic
gradients across the endothelium, and further dem-
strates an absence of lactate toxicity to the tissue.

The effects of tears-side NaL (Fig. 10) or excess
NaCl (Fig. 11) appear similar, since either agent de-
swells corneas at 5 mM as predicted by Klyce and
Russell.23 In two compartment systems (corneas
bathed with silicone oil replacing the aqueous bath)\textsuperscript{21} and Wilson et al\textsuperscript{22} demonstrated
more pronounced osmotic effects across the
epithelium with 10–46 mOsm/L gradients of NaCl,
glucose, or other solutes. However, since the experi-
ments in Figures 9 and 10 involved three compart-
ments (aqueous, stroma, and tears) and unstirred
layers, more complex kinetics are involved, and os-
motic gradients across the epithelium may be re-
duced due to fluid exchange across the endothelium.

Implications for Hypoxic Corneal Edema

It appears that in vitro, and in the concentrations
examined, the effects of neutral NaL are similar in all
respects to excesses of NaCl, and at these concentra-
tions, lactate has no acute toxic effect on the epithe-
lum, endothelium, or stroma to influence corneal
thickness. This contrasts with the toxic effects of
neutral lactate in cardiac tissue.\textsuperscript{6–8} Corneas loaded
with NaL do swell osmotically, however. Thus, neu-
tral lactate accumulation in the stroma can osmoti-
cally account for hypoxic edema as suggested by
Klyce.\textsuperscript{4} Although the lactate accumulation can
probably explain edema, the other consequences of cor-
neal hypoxia (morphologic changes\textsuperscript{10–12} and aci-
dosis\textsuperscript{24–26}) warrant further study for their etiologies
and effects on this tissue.

Key words: cornea, edema, lactate, rabbit, specular micro-
copy, stroma

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