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Effects of sympathetic denervation on the hyaluronan content of the anterior segment in the normal and traumatized rabbit eye

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ABSTRACT.
Purpose: **To determine whether there is any involvement of sympathetic nerves in the regulation of ocular hyaluronan production in the normal and traumatized rabbit iris.**
Methods: **Unilateral sympathetic denervation was performed by removing the right superior cervical ganglion. Hyaluronan concentrations in the iris and aqueous were measured with a radiometric assay at various time intervals after denervation. Peripheral iridectomy was also performed in both denervated and non-denervated eyes.**
Results: **Hyaluronan concentrations in the iris tissue after denervation were observed to have increased after 1 day, reaching a peak of $129.6 \pm 5.7\,\mu g/g$ wet weight at day 3. Two weeks later, hyaluronan concentrations had fallen back to normal levels. Ocular trauma with peripheral iridectomy in denervated eyes caused an increase of hyaluronan content of up to $253.5 \pm 30.5\,\mu g/g$ wet weight, which was not significantly different from hyaluronan concentrations observed after the same trauma in non-denervated eyes.**
Conclusion: **Cervical sympathetic denervation results in a moderate increase of the hyaluronan content in the rabbit iris and does not appear to influence the hyaluronan response of the iris to trauma.**

Key words: hyaluronan – iris – aqueous humor – sympathetic denervation – trauma response

Hyaluronan (hyaluronic acid, sodium hyaluronate) is a non-sulphated linear polysaccharide. It is richly distributed throughout the body, with the highest concentrations found in connective tissue. High molecular weight exogenous hyaluronan is widely used in ophthalmic anterior segment surgery because of its protective effects on ocular tissues. We are, therefore, interested in examining the biology of endogenous hyaluronan in some detail, and we here report the influence of sympathetic nerves on trauma response.

Endogenous hyaluronan has been identified throughout most of the eye tissues, including the vitreous (Österlin & Jacobson 1968; Laurent 1982), the retina (Eggli & Graber 1996), the ciliary body, sclera, conjunctiva and ciliary zonules (Lütjen-Drecoll et al. 1990), the corneal endothelium and the iris (Lütjen-Drecoll et al. 1990; Molander et al. 1993; Koralewska-Makár et al. 1998).

The physiological role of endogenous hyaluronan appears to be associated with trauma and inflammation. In our previous studies, we were able to show a rapid increase of hyaluronan concentration in the iris after peripheral iridectomy and after laser irradiation (Koralewska-Makár et al. 1998, 2001). The changes in aqueous hyaluronan concentration corresponded to similar changes in the iris. In another study, we were able to demonstrate *in situ* production of hyaluronan by normal and wounded iris tissue *in vivo* as well as in culture (Koralewska-Makár et al. 2000). The iris appears to be the most important source of aqueous hyaluronan.

The sympathetic innervation present in the anterior segment of the eye (Ehinger et al. 1969; Ruskell 1982) influences a number of important processes. Sympathetic denervation of the eye decreases proliferation of normal and wounded corneal epithelium in rats (Jones & Marfurt 1996), enhances the response of the eye to ocular injury (neutral formaldehyde: Krootila et al. 1987; laser burn: Unger 1990) and induces heterochromia (depigmentation) of the iris in pigmented rabbits (Ehinger et al. 1969; Ruskell 1982).

Because the iris is richly supplied with sympathetic nerve fibres (Ehinger et al.

1969; Ruskell 1982), unilateral surgical sympathectomy was performed in order to determine whether there is any involvement of sympathetic nerves in the regulation of ocular hyaluronan production in both normal and traumatized rabbit irisies.

Material and Methods

Pigmented adult rabbits of mixed strain were used in this study. All animals were treated according to ARVO regulations for the use of animals in research. The experiments were monitored by the Swedish Board for Animal Experimental Ethics. Animals were anaesthetized with a 3 : 1 mixture of ketamine (50 mg/mL; Ketalar®; Parke Davis, Solna, Sweden) and xylazine (20 mg/mL; Rompun®; Bayer, Göteborg, Sweden). An initial intramuscular injection of 1 mL/kg of the mixture was followed by subsequent injections as required.

Unilateral sympathetic denervation was performed by removing the right superior cervical ganglion. A careful dissection of structures was carried out to ensure that the cervical sympathetic ganglia were clearly identified. The animals were killed at 1 day, 3 days and 2 weeks after surgery with an intravenous overdose of pentobarbital. Each group consisted of six or seven animals unless stated otherwise.

In order to investigate the influence of sympathetic denervation on hyaluronan response in an injured iris, we performed a peripheral iridectomy of the iris in six denervated eyes 2 weeks after the removal of the superior cervical ganglion. These animals were killed 2 days later. Eight normal rabbits, four of which had undergone peripheral iridectomy, served as controls.

All rabbits were operated on the right side (ganglionectomy, peripheral iridectomy), leaving the left eye available as a control eye. The eye trauma (peripheral iridectomy) was performed in the upper iris half (at 12 o'clock) with scissors after the 3 mm corneal incision had been made with a keratome. The wound was closed with a 10-0 nylon suture.

The aqueous samples were collected with a 30-gauge needle inserted through the limbal cornea with the eye still in its socket. The cornea was then removed and iris tissue was obtained with scissors. The iris samples from both the unoperated control animals and the rabbits that had undergone iridectomy were divided into upper and lower halves. The aqueous samples were frozen immediately and stored at $-20\,°C$. They were later analysed for hyaluronan and total proteins without pretreatment. The iris samples were weighted wet and were also stored at $-20\,°C$.

The iris samples were freeze-dried for 48 h and then treated with pronase, which facilitates the subsequent extraction of hyaluronan from the tissue (Molander 1994; Johnsson et al. 1998). Hyaluronan concentrations were measured using a radiometric assay based on specific hyaluronan binding protein (Pharmacia HA test 50; Pharmacia & Upjohn, Uppsala, Sweden) (Brandt et al. 1987). Total protein concentration was determined by a turbidimetric procedure using benzethonium chloride precipitation as described by Luxton et al. (1989) and modified for automated analysis using a Hitachi 917 multipurpose analysis machine.

The aqueous flare was measured with a photoelectric instrument (Bengtsson et al. 1975) and expressed in arbitrary units. There is known to be a strong correlation between protein concentration and flare density (Anjou & Krakau 1961).

All results are given as the average $\pm$ SEM (standard error of the mean). Student's t-test was used for statistical analyses, and the difference between unpaired groups was considered significant when $p < 0.05$.

Results

Iris hyaluronan

Hyaluronan concentrations in the irides of normal, non-treated rabbits were found to be $40 \pm 5.0\,\mu g/g$ wet weight. There were no statistically significant differences between the upper and lower halves of the irides or the right and left eyes.

In the denervated right eyes, hyaluronan concentrations in the iris were noted to have increased after 1 day, reaching a maximum of $129.6 \pm 5.7\,\mu g/g$ wet weight 3 days after surgery, as assayed in the upper iris halves. This increase is statistically significant in comparison with observations of the upper iris halves in the normal control animals ($p = 0.0002$). Hyaluronan concentrations had returned to normal by 2 weeks after denervation. The iris hyaluronan of the left eyes remained unchanged.

In the group of animals that underwent peripheral iridectomy 2 weeks after sympathetic denervation, iris hyaluronan increased again in the upper iris halves, reaching $253.5 \pm 30.5\,\mu g/g$ wet weight 2 days after ocular surgery ($p = 0.0032$ compared to normal controls). In the non-denervated eyes, iris hyaluronan reached $296.3 \pm 36.2\,\mu g/g$ wet weight 2 days after peripheral iridectomy ($p = 0.0027$ compared to normal controls). There was no statistically significant difference between the increased hyaluronan
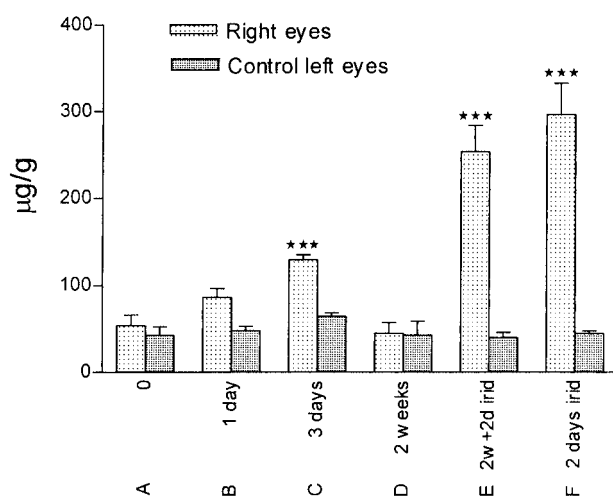

Fig. 1. The course of iris hyaluronan concentrations at different times before and after superior cervical sympathectomy (column pairs A to D). Column pair E shows concentrations 2 weeks after superior cervical sympathectomy plus an additional 2 days after peripheral iridectomy. Column pair F shows concentrations 2 days after iridectomy in non-denervated animals. Asterisks show statistical significances for difference when compared with non-denervated eyes (*: $p < 0.05$, **: $p < 0.02$, ***: $p < 0.01$).

concentrations after iris trauma in the denervated and non-denervated eyes. There were no changes in the contralateral left eyes (Fig. 1.)

The significantly higher concentrations of hyaluronan after iris trauma were found exclusively in the upper (iridectomized) halves of both denervated and non-denervated eyes. Hyaluronan concentrations in the lower halves did not show any significant differences from those of the normal control eyes in any of the different groups (traumatized denervated eyes: $44.17 \pm 10.6 \mu g/mL$; traumatized non-denervated eyes: $67.8 \pm 13.5 \mu g/mL$; contralateral left eyes in both denervated and non-denervated animals: $58.17 \pm 12.5 \mu g/mL$ and $35 \pm 4.7 \mu g/mL$, respectively).

Aqueous hyaluronan and aqueous flare proteins

Hyaluronan concentrations in the aqueous increased slightly in right eyes 1 day after denervation, from an average normal concentration of $0.79 \pm 0.06 \mu g/mL$ to $1.15 \pm 0.1 \mu g/mL$ ($p = 0.0491$). No significant difference from normal values was found in hyaluronan levels 3 days and 2 weeks after removal of the superior cervical ganglion.

In the denervated eyes, hyaluronan concentrations increased to $2.31 \pm 0.11 \mu g/mL$ 2 days after peripheral iridectomy ($p < 0.0001$ compared to normal eyes). This was lower ($p = 0.0272$) than the level found in non-denervated eyes 2 days after the same type of iris trauma ($2.72 \pm 0.1 \mu g/mL$; $p < 0.0001$ compared to normal eyes). The contralateral left eyes did not show any significant changes in aqueous hyaluronan (Fig. 2.).

Aqueous protein concentrations increased rapidly to a maximum of $16.6 \pm 2.5 g/L$ 1 day after denervation. This increase is statistically significant ($p = 0.0027$) when compared to the aqueous protein concentrations found in the normal control eyes ($0.43 \pm 0.08 g/L$). These concentrations subsequently decreased swiftly, reaching normal levels by day 3. Two days after peripheral iridectomy was carried out in denervated eyes, protein concentrations had increased again to $2.53 \pm 0.5 g/L$ ($p = 0.0208$ compared to normal eyes). This is not statistically different from the levels found following the same trauma in non-denervated eyes ($2.09 \pm 0.1 g/L$). Aqueous protein levels in contralateral left eyes remained unchanged (Fig. 3.).

Changes in the aqueous flare were similar to those noted in levels of aque-ous proteins, with a normal value of 1.75 ± 0.5 arbitrary units and a high peak value of 24.5 ± 4.5 units 1 day after denervation ($p = 0.0039$ compared to normal eyes). Two days after iridectomy, the aqueous flare had again increased in both denervated eyes (11.3 ± 1.1 units, p < 0.0001) and non-denervated eyes (8.5 ± 1.0 units, $p = 0.0007$). However, there was no statistically significant difference between the increases in denervated and non-denervated eyes. Contralateral left eyes did not show any significant changes (Fig. 4.).

Two days after the iris trauma (peripheral iridectomy), the relatively low levels of protein concentration in the aqueous humor and low levels of aqueous flare response in both denervated and non-denervated eyes were, as expected, already decreasing. The blood-aqueous barrier recovers around 75 min after trauma in both normal and denervated eyes (Krootila et al. 1987).
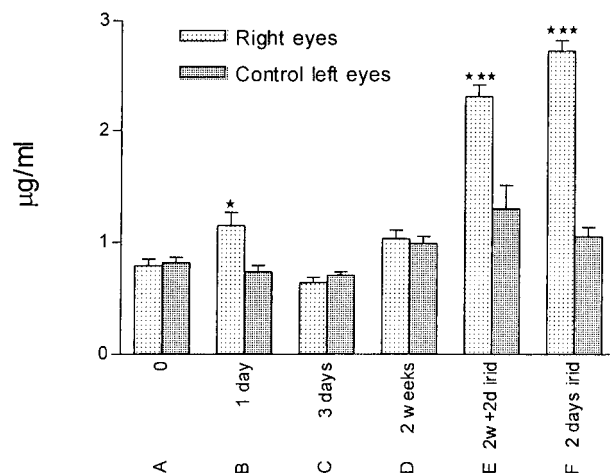

Fig. 2. The course of aqueous hyaluronan concentrations at different times before and after superior cervical sympathectomy (column pairs A to D). Column pair E shows concentrations 2 weeks after superior cervical sympathectomy plus an additional 2 days after peripheral iridectomy. Column pair F shows concentrations 2 days after iridectomy in non-denervated animals. Asterisks indicate statistically significant higher levels than seen in non-denervated eyes (*: p <0.05, **: p <0.02, ***: p <0.01).
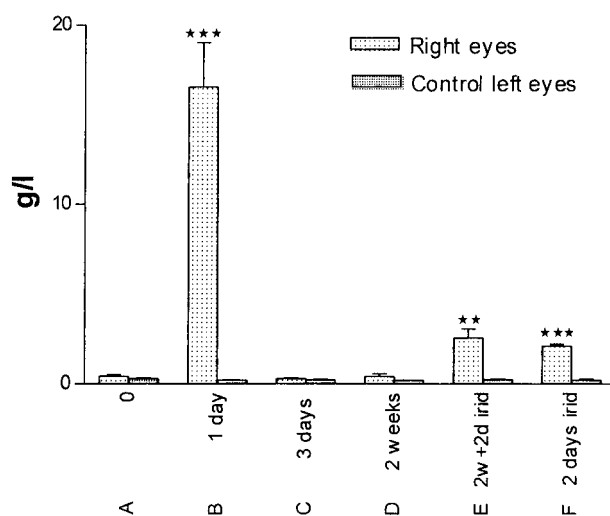

Fig. 3. The course of aqueous protein concentrations at different times before and after superior cervical sympathectomy (column pairs A to D). Column pair E shows concentrations 2 weeks after superior cervical sympathectomy plus an additional 2 days after peripheral iridectomy. Column pair F shows concentrations 2 days after iridectomy in non-denervated animals. Asterisks indicate statistically significant higher levels than seen in non-denervated eyes (*: p <0.05, **: p <0.02, ***: p <0.01).
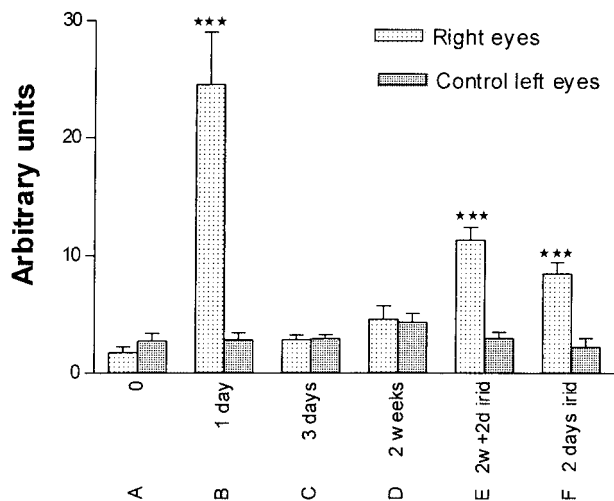
Fig. 4. The course of aqueous flare response at different times before and after superior cervical sympathectomy (column pairs A to D). Column pair E shows response 2 weeks after superior cervical sympathectomy plus an additional 2 days after peripheral iridectomy. Column pair F shows response 2 days after iridectomy in non-denervated animals. Asterisks indicate the statistically significant higher levels than seen in non-denervated eyes (*: $p < 0.05$, **: $p < 0.02$, ***: $p < 0.01$).

Discussion

Sympathetic denervation of the eye induces an acute response similar to that induced by trauma, and later enhances the response to ocular trauma (Krootila et al. 1987; Unger 1990). This made it interesting to investigate to what extent the sympathetic nerves may influence hyaluronan production in both normal and traumatized eyes. Moreover, the fact that the iris sympathetic supply is entirely ipsilateral and that there is no reinnervation of the iris after unilateral removal of the superior cervical ganglion (Ehinger et al. 1969; Ruskell 1982), allowed us to investigate the influence of sympathetic nerves on hyaluronan production in the iris. There is to our knowledge no prior research into the subject.

Eggli & Graber (1996) described hyaluronan as occurring in unmyelinated iris nerve fibres in rats. Electron microscopic studies by Roth & Richardson (1969) demonstrated fine structural changes in adrenergic axons from 18 to 24 h after ganglionectomy, indicating that the initial rise in aqueous and iridic hyaluronan may be caused by a release directly from nerve endings. However, it is also well-known that degenerating nerve fibres release numerous other bioactive substances, including prostaglandins and certain neuropeptides (Neufeld et al. 1973; Unger 1990). These may also be responsible for an increase in production of hyaluronan in the iris and might explain why this increase remains for a slightly longer period than does the increase in the aqueous humor. Exogenous prostaglandins have been shown to stimulate hyaluronan synthesis in synovial cell cultures (Castor 1975).

The protracted increase of iris hyaluronan concentration in comparison with aqueous hyaluronan in response to iris trauma has been demonstrated already in our previous studies (Koralewska-Makár et al. 1998, 2001). It therefore appears that, in general, hyaluronan retention is more prolonged in iris tissue than in anterior chamber aqueous humor, irrespective of the cause of the increased concentration.

Two weeks after denervation, hyaluronan concentrations in the iris had decreased to normal levels, thereby implying that the sympathetic nerves have only a moderate influence on iris hyaluronan content. This does not mean that they cannot influence hyaluronan levels over longer periods of time. Canine femoral arteries have been observed to show a decrease in hyaluronan content 20–50 days after lumbar sympathectomy (Marinescu et al. 1968).

After superior cervical ganglion excision, the eye develops hypersensitivity to trauma (Unger 1977; Unger et al. 1981; Krootila et al. 1987; Unger 1990). Moreover, the concentration of hyaluronan in the iris increases after an iris trauma (peripheral iridectomy or laser irradiation), with maximum levels seen at day 2 (Koralewska-Makár et al. 1998, 2001). In the present study, concentrations of hyaluronan in the iris 2 days after ocular surgery were not significantly different in denervated and non-denervated eyes. The current experiments therefore do not support any assumption that sympathectomy will induce any increased propensity of the iris to respond to trauma by increasing its hyaluronan content.

The increased hyaluronan concentrations after iris trauma were found in upper iridectomy halves in both denerved and non-denervated eyes. This finding agrees with our previous histochemical and quantitative concentration studies, which showed only a very localized increase in hyaluronan at the trauma site (Koralewska-Makár et al. 1998). Moreover, direct iris trauma (iridectomy) seems to cause much more trauma to the iris than sympathetic denervation and results in higher concentrations of hyaluronan in both the iris tissue and the aqueous humor.

In conclusion, this study demonstrates that cervical sympathectomy results in comparatively moderate and short-lived hyaluronan content increases in the rabbit iris and aqueous humor. These increases are probably mostly due to the denervation degeneration of iris neurons, which may release neuronal hyaluronan as well as several different substances including prostaglandins known to stimulate *de novo* synthesis of hyaluronan in connective tissue. The sympathetic denervation does not appear to influence the iris hyaluronan response to trauma (iridectomy) or the distribution of hyaluronan in the iris tissue after trauma. From a clinical point of view, these results raise no particular concerns about the status of the sympathetic innervation of the eye in anterior segment surgery.

Acknowledgements

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