Oxidative Stress in Keratoconus?

Emma Arnal,1 Cristina Peris-Martínez,1,2 Jose Luis Menezo,1 Siv Johnsen-Soriano,1 and Francisco Javier Romero1,5

PURPOSE. The purpose of this study was to establish the alterations of oxidative stress-related markers in keratoconus (KC) corneas.

METHODS. A total of 6 healthy and 11 ectatic corneas (7 KC and 4 post-LASIK) were studied. Different oxidative stress-related markers were determined to assess their implication in the KC pathophysiology. Total antioxidant capacity and total nitrites present in the samples were assayed. Furthermore, lipid peroxidation products and the glutathione contents were determined, together with 4-hydroxynonenal (4-HNE) immunohistochemistry, to establish the relationship between KC and oxidative stress.

RESULTS. The antioxidant capacity and glutathione content in KC corneas were decreased significantly when compared with healthy corneas. Moreover, the total nitrates and lipid peroxidation were significantly elevated in the corneas with KC when compared with the controls. There was a statistically significant difference in the amount of HNE-positive cells in KC corneas when compared with healthy corneas by immunohistochemistry. Post-LASIK ectatic corneas and KC corneas showed similar results.

CONCLUSIONS. The increased levels of oxidative stress markers and the decreased antioxidant capacity and antioxidant defenses in KC corneas, as well as in the post-LASIK ectatic corneas, indicate that oxidative stress might be involved in the development of this disease and may provide new insights for its prevention and treatment in the future. (Invest Ophthalmol Vis Sci. 2011;52:8592–8597) DOI:10.1167/iovs.11-7732

Keratoconus (KC) is a significant clinical problem worldwide and a leading indication for corneal transplantation. KC is a progressive, noninflammatory corneal ectasia that results in protrusion and thinning due to a weakening of the cornea.1 It classically manifests in the teenage years to young adulthood and leads to a variable decrease in the quality of vision and ocular discomfort.2 The weakened cornea is one of the most challenging conditions for surgeons to recognize before performing LASIK (laser in situ keratomileusis) or to treat after LASIK.3 LASIK is one of the most common refractive surgical procedures for the treatment of myopia. The molecular pathogenesis of KC is poorly understood and to understand how to strengthen the cornea, one must first understand how the cornea is weakened by keratoectasia and KC. Previous reports suggested that oxidative stress may be involved in KC.4–8 It is commonly known that the accumulation of reactive oxygen species (ROS) can damage cells by reacting with proteins, DNA, and membrane phospholipids. Normally, the cornea’s natural antioxidant enzymes eliminate the ROS before they damage cells; these include superoxide dismutase, catalase, glutathione reductase, and glutathione peroxidase.9,10 but in the disease state, ROS may overwhelm cellular defenses and promote cell damage.

Cells can also be damaged by subproducts formed during ROS-induced lipid peroxidation11,12 and the release of different reactive aldehydes, such as malondialdehyde (MDA) and 4-hydroxy-2, 3-trans-nonenal (HNE).13,14 Aldehydes are relatively stable compared with free radicals and can diffuse to attack distant target sites. These aldehydes are highly reactive and can covalently interact with proteins and DNA to form adducts that alter signal transduction, gene expression, and proliferation. Aldehydes disrupt the membranes of lysosomes and cells releasing lysosomal proteolytic enzymes, including cathepsins.14 Former reports have demonstrated that KC corneas have increased levels of cathepsin-B and -G, and lysosomal enzymes (acid esterases, acid phosphatases, and acid lipases).15 but there are no data available regarding the presence of lipid peroxidation products in this tissue.

HNE is a prominent aldehyde generated during lipid peroxidation, and is thought to play a major role in cell dysfunction and death in disorders ranging from atherosclerosis,16,17 diabetes, and retinal degenerative disorders.18 HNE can modify proteins on cysteine, lysine, and histidine residues and such modifications can impair protein function and promote protein aggregation. For example, HNE has been shown to impair the function of ion-motive adenosine triphosphatases (ATPases), glucose, and glutamate transporters, and guanosine triphosphate (GTP) binding proteins in experimental models of degenerative disorders19,20 and even inhibit glutathione peroxidase activity.21

Although some antioxidant enzymatic activities and protein levels have been examined in normal and KC corneas.4,5,7 the role of oxidative stress and HNE in KC corneas is not clear. Data reported herein are novel and may provide new insights into the pathophysiology of corneal ectasia.

METHODS

A total of 17 human corneal buttons obtained at the Fundación Oftalmológica del Mediterráneo (FOM-Valencia, Spain) were studied (Table 1). Eleven ectatic corneas (seven KC and four ectatic corneas associated with LASIK surgery) were analyzed within 24 hours after penetrating keratoplasty. Age-matched normal corneas (n = 6) were used as a control group from healthy donors (the corneal rim, which is not used for corneal transplant) within 24 hours after death. Informed consent was obtained from all participants or relatives, and the study was performed according to the tenets of the Declaration of Helsinki for research involving human subjects.
Antioxidant Capacity

The antioxidant capacity was measured with a commercial kit (Antioxidant Assay Kit, Cayman, MI) that is used to measure the total antioxidant capacity of the different samples (Fig. 1). The assay relies on the ability of the antioxidants in the sample to inhibit the oxidation of 3-ethylbenzotiazolin-6-sulfonic acid (ABTS) to ABTS+ by metmyoglobin. The amount of ABTS+ can be monitored by reading the absorbance at 405 nm which is proportional to its concentration.

Level of Nitrates

To measure the total nitrates, a commercial kit was used (Parameter, Total Nitrite, R&D Systems, Oxford, UK). The principle of this assay is the determination of nitric oxide (NO) concentrations based on the enzymatic conversion of nitrate to nitrite. The amount of total nitrates can be monitored by reading the absorbance at 540 nm which is proportional to the NO concentration.

Lipid Peroxidation

The lipid peroxidation was measured with a commercial kit (Lipid Peroxidation Microplate Assay Kit, Oxford Biomedical Research, Rochester Hills, MI) following the manufacturer’s instructions (see Fig. 3). This assay is based on the reaction of two molecules of a chromogenic reagent, N-methyl-2-phenylindole, with one molecule of malondialdehyde (MDA), at 45°C, to yield a stable chromophore with a maximal absorbance at 586 nm. The amount of MDA can be monitored by reading the absorbance at 586 nm which is proportional to its concentration.

Glutathione Levels

The concentration of total glutathione (GSH) was measured with a commercial kit (NWLSS Glutathione Assay, Northwest Life Science, Vancouver, WA) following the manufacturer’s instructions (see Fig. 4).

RESULTS

Antioxidant Capacity

The antioxidant capacity in keratoconus corneas was decreased significantly (0.29 ± 0.07 mM/mg protein) when compared with normal corneas (0.89 ± 0.27 mM/mg protein, P < 0.05 vs. control). This antioxidant capacity in ectasia associated with LASIK patients, was also decreased significantly (0.40 ± 0.086 mM/mg protein) when compared with normal corneas (see Fig. 1). However, there were no significant differences when keratoconus corneas (0.29 ± 0.07 mM/mg protein) were compared with ectasia associated with LASIK corneas (0.40 ± 0.086 mM/mg protein, P > 0.05).
Total Nitrites

Total nitrites were significantly elevated in the corneas with keratoconus (0.87 ± 0.27 μmol/mg protein) and ectasia associated with LASIK (0.61 ± 0.10 μmol/mg protein), when compared with the control ones (0.42 ± 0.15 μmol/mg protein, \( P < 0.05 \) vs. control) (Fig. 2).

Lipid Peroxidation

The concentrations of the lipid peroxidation product MDA in the corneas of the different groups showed an increase with a statistical significant difference \((P < 0.05)\) between keratoconus corneas (0.58 ± 0.11 μmol of MDA/mg protein) and LASIK corneas (0.42 ± 0.1 μmol of MDA/mg protein), when both groups were compared with the control one (0.28 ± 0.05 μmol of MDA/mg protein). Again, no significant difference between keratoconus and LASIK group was observed (Fig. 3).

Glutathione

GSH contents were decreased in both the KC (0.29 ± 0.06 μmol/mg protein) and ectasia associated with LASIK corneas groups (0.31 ± 0.079 μmol/mg protein), when compared with the control group (0.46 ± 0.082 μmol/mg protein). This tendency was observed in both groups with a statistical difference \((P < 0.05)\). However, there is no statistical difference \((P < 0.05)\) between the KC corneal group and the ectasia associated with LASIK group (Fig. 4).

HNE Immunohistochemistry

The oxidative marker HNE was used to confirm occurrence of lipid peroxidation. The corneas showed a significant increasing amount of HNE-positive stained cells \((P < 0.05)\) (Fig. 5A). The same observation was shown in the fluorescence-stained HNE cells (Fig. 5B). No marked difference in HNE staining could be observed between KC and LASIK groups.

DISCUSSION

Oxidative stress is a very relevant pathway in the pathologic processes associated with cardiovascular, diabetes, and retinal diseases. Lipid peroxidation and reactive aldehydes are associated with chronic liver diseases, aging, amyotrophic lateral sclerosis, ischemia, and diabetes mellitus. Herein, we examined lipid peroxidation and other oxidative alterations in diseased ectatic corneas and the presence of 4-HNE by immunohistochemistry.

Corneal cells are capable of expressing isoforms of the nitric oxide synthase (NOS), suggesting that significant quantities of nitric oxide (NO) are produced physiologically in the cornea. Because the cornea absorbs approximately 80% of the incident ultraviolet B (UVB) light, there is a potential for generating significant amounts of free radicals and ROS. Nitric oxide is a mediator in many complex cellular processes in ocular tissues. Increased levels of nitric oxide have cytotoxic effects that are mediated by peroxynitrite, which can be localized by the accumulation of a specific marker, nitrotyrosine. Recently, other studies reported that KC corneas have elevated levels of inducible nitric oxide synthase (iNOS) and accumulate nitrotyrosine when compared with normal corneas or corneas affected by other diseases. The expression of iNOS is usually associated with the generation of high levels of nitric oxide, which in turn can react with superoxide molecules to form peroxynitrite. In the cornea, endothelial NOS (eNOS) activity has been demonstrated in the epithelium and endothelium. The NO/cGMP pathway may be important in preventing corneal edema and maintaining normal corneal thickness, and nitric oxide has been shown to be involved in inflammation, angiogenesis, and the maintenance of corneal thickness. These previous results agree with the results obtained herein; Figure 2 shows a higher amount of total nitrites when compared with healthy corneas, and strongly supports the proposal that reactive nitrogen species (nitric oxide and peroxynitrite) might be involved in keratoconus etiopathology.

Lipid peroxidation may result from UV-induced oxidative destruction of cell membranes and the formation of cytotoxic aldehydes. These aldehydes can induce enzymatic activity im-

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Total nitrites in control corneas and corneas with keratoconus and ectasia after LASIK \((P < 0.05)\).

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Malondialdehyde (MDA) concentration in the different groups of corneas \((P < 0.05)\).

![Figure 4](https://example.com/figure4.png)

**Figure 4.** GSH content in all cornea groups studied \((P < 0.05)\).
pairments, inhibition of DNA/RNA/protein synthesis, and other damaging events. To our knowledge this is the first study to document the presence of the toxic aldehyde HNE in human diseased ectatic corneas and the possible relationship between KC disease and the antioxidant capacity, especially the reduced glutathione content, in this tissue. In normal corneas, high levels of aldehyde dehydrogenase 3 (ALDH3) and SOD are present whose function is presumably to absorb UV and scavenge both free oxygen radicals (SOD) and the generated aldehydes (ALDH3). In this respect, a decrease of SOD1 expression has previously been demonstrated in KC corneas. Previous studies and immunohistochemical data demonstrated the presence of malondialdehyde (MDA) and nitrotyrosine (a marker for peroxynitrite, a cytotoxic product of the nitric oxide pathway) within the KC cornea compared with normal corneas or other corneal diseases.

The toxicity of HNE and its mechanisms of toxicity are clearly defined in culture systems. Little evidence of HNE staining is observed in normal corneas; however, all the disease groups examined here showed significant and distinct patterns of 4-HNE staining (Fig. 5) confirming that HNE might play a role in this until now theoretically noninflammatory corneal disorder (i.e., keratoconus). The increased formation of total nitrates and HNE in KC corneas (and, to a lesser extent, in ectasia associated with LASIK surgery) allows the proposal of a relevant role of free radicals in their pathogenesis. In our study, KC and ectasia associated with LASIK results are similar. Ectasia is an uncommon but dreaded complication of LASIK surgery. Although the incidence of serious complications is relatively low, the visual consequences in some cases are severe. Etio-pathogenesis of corneal ectasia associated with LASIK is still controversial. There are some cases of post-LASIK ectasia pub-
lished in patients with apparently “normal” corneas, but in the majority of these cases, patients are found to have risk factors for ectasia, like for instance preoperative myopia greater than ~8 diopters, undiagnosed previous KC, and residual stromal bed thickness after surgery < 250 μm.

Such a mechanism could, over a period, cause alterations of the stromal collagen molecules in KC, perhaps making them more susceptible to digestion by activated enzymes, thus leading to stromal thinning. In addition to the effect on proteins, both nitric oxide (NO) and peroxynitrite are involved in multiple cytotoxic pathways. Both NO and peroxynitrite are toxic to DNA, leading to mutations and strand breaks. In this context, it is important to note that sustained exposure to high levels of NO or peroxynitrite can trigger apoptosis, and increased apoptotic activity has been reported in keratoconus corneas. Further research on the apoptotic pathway in KC is certainly a relevant issue.

In conclusion, the data herein show unique patterns of HNE distribution in KC and ectasia after LASIK and an accumulation of products of oxidative stress (nitrates) in this tissue. The excessive amounts of both these substances and the reduction observed of the natural antioxidant defenses (GSH, antioxidant capacity) in the KC corneas support the hypothesis that oxidative damage may play a role in the pathogenesis of this corneal disease.

**CONCLUSION**

The increased levels of oxidative stress markers and the decreased antioxidant capacity and antioxidant defenses in keratoconus corneas indicate that oxidative stress may be involved in the development of this pathology and these results may provide new insights for the prevention and treatment of this disease in the future.

**Acknowledgments**

The authors thank Leticia Gómez and Diana Martínez at FOM, Valencia, Spain, for their excellent technical assistance.

**References**