Corneal cross-linking combines short wavelength light and a chromophore to induce specific changes in the collagen of the corneal stroma. The first change that was investigated in detail was the increase in the biomechanical stability of the cornea, and this specific property of CXL was used to develop therapeutic strategies for corneal ectasias, like keratoconus and postoperative ectasia. Another CXL-mediated effect includes changes in the tertiary structure that affect corneal packing density and swelling behavior. This property was used to develop treatment modalities for bullous keratopathy, early Fuchs’ dystrophy, and corneal edema. Finally, CXL increases the corneal resistance to enzymatic digestion by steric hindrance, a mechanism used to treat rosacea-mediated or trophic peripheral ulcers. Here, the UV-A irradiation must be performed in a decentered manner to cover the area of active disease, and a part of the limbal area will be exposed to short-wavelength UV-A light.

To investigate the potential effect of UV-A light and riboflavin on the regenerative capacity of the limbal epithelial stem cells, we irradiated the cornea and limbus of rabbits in vivo, using the standard fluence of 5.4 J/cm² currently applied clinically, and also a fluence twice as high as the current clinical setting (10.8 J/cm²).

Materials and Methods

Animals

All procedures concerning animals in this study adhered to the ARVO resolution for the care and use of animals in vision research. Three- to 4-month-old male New Zealand White rabbits (Crl:KBL) were used. All animals displayed a white-to-white diameter between 11 and 12 mm, and central corneal thickness (CCT), as determined by ultrasound pachymetry (Tomey SP-2000; Tomey Corporation, Nagoya, Japan), was between 600 and 700 μm.

Cross-Linking Procedure

Animals were anesthetized using an intramuscular injection of 1.5 mL ketamine hydrochloride 10% (35 mg/kg of body weight) and 0.5 mL xylazine hydrochloride (5 mg/kg of body weight).
Effect of Standard and High-Fluence CXL

TABLE. Overview on the Experimental Setup Using Two Different Fluences (5.4 and 10.8 J/cm²) and Two Different Irradiation Zones

<table>
<thead>
<tr>
<th>Group</th>
<th>No. of Animals</th>
<th>Fluence (Intensity × Time)</th>
<th>Irradiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>5.4 J/cm²</td>
<td>Cornea only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(9 mW/cm² for 10 min)</td>
<td>(7 mm)</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>10.8 J/cm²</td>
<td>Cornea only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(9 mW/cm² for 20 min)</td>
<td>(7 mm)</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>5.4 J/cm²</td>
<td>Cornea and limbus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(9 mW/cm² for 10 min)</td>
<td>(13 mm)</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>10.8 J/cm²</td>
<td>Cornea and limbus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(9 mW/cm² for 20 min)</td>
<td>(15 mm)</td>
</tr>
</tbody>
</table>

and paropracaine eye drops were applied topically. CXL was performed as described previously. Brieﬂy, corneas were de-epithelialized mechanically in a diameter of 10 to 11 mm, leaving a margin of 1 mm to the limbus. Isotonic 0.1% riboﬂavin solution containing 20% dextrane (MedioCross D Solution; Peschke Meditrade GmbH, Hünenberg, Switzerland) was instilled every 2 minutes for 25 minutes without the use of a speculum to avoid corneal dehydration and stromal thinning. Corneal thickness was veriﬁed immediately before irradiation by ultrasound pachymetry (Tomey SP-2000; Tomey Corporation), and all corneas used in the experiments showed no more than ±10% variation of central thickness when compared with thickness before riboﬂavin instillation.24 The Table shows experimental irradiation and ﬂuence settings: UV-A irradiation was performed in the right eye at 365 nm with a ﬂuence of 5.4 J/cm² (3 mW/cm² for 30 minutes) and 10.8 J/cm², corneas showed a partial re-epithelialization at 24 hours (Fig. 1B) and a complete re-epithelialization at 72 hours (Fig. 1C) after CXL. Corneas that were treated using the standard ﬂuence of 5.4 J/cm² (data not shown) and the unirradiated controls (Figs. 1E, 1F) showed a re-epithelialization speed at 24 hours and 72 hours, similar to the one observed at 10.8 J/cm² (double-standard ﬂuence).

Light microscopic analysis of the cornea and the limbal area was performed at 4 weeks after CXL. Hematoxylin and eosin staining showed a regular morphology of the corneal stroma as well as of the corneal and limbal epithelial cells after irradiation at a ﬂuence of 5.4 J/cm² (Figs. 2C, 2D) and 10.8 J/cm² (Figs. 2E, 2F).

Immunohistochemical analysis of the corneal-speciﬁc marker cytokeratin 3 (K3) showed similar expression in all layers of the corneal epithelium and in the suprabasal limbal epithelium for all conditions tested (Figs. 2F–K).

The p63, an important transcription factor for epithelial development and homeostasis and a putative corneal epithelial stem cell marker was analyzed after CXL with 5.4 J/cm² and 10.8 J/cm² and in unirradiated controls.25 In all conditions tested, p63 showed a similar pattern with distinct expression in the basal cells and, to a lesser extent, in the superficial layers of the limbal epithelium, and absence of staining in the corneal epithelium (Figs. 2L–P).

DISCUSSION

Currently, the most common indication for CXL is classic progressive keratoconus with stromal thinning and bulging, usually occurring in the midperiphery of the cornea, 3 to 4 mm from the center. Accordingly, irradiation is performed in a centered fashion over an area of 8 to 9 mm. Besides keratoconus, CXL was successfully applied in a number of other corneal diseases like PMD, Terrien’s marginal degeneration, and rosacea-mediated or trophic peripheral ulcers.20–22,26 All conditions have in common that they affect the periphery of the cornea rather than the center or the midperiphery. Here, irradiation must be centered and applied in an eccentric fashion. Partial irradiation of the limbus is unavoidable, even when attempts are made to shield the limbus.

Concerning PMD, only a few cases treated by CXL have been reported in the literature so far. Steppat and colleagues (Steppat M, et al. Invest Ophthalmol Vis Sci 2008;49:ARVO E-Abstract 4342) reported on 13 eyes of eight patients with PMD and a clinical follow-up of 18 months. They found an arrest of PMD progression in all eyes in the absence of side effects. In particular, no clinical signs of limbal stem cell insufﬁciency were observed. Spadec22 described a 43-year-old patient with bilateral PMD who underwent successful CXL in his left eye. Hassan and colleagues26 reported on a similar case of bilateral PMD where one eye was successfully treated with CXL. Kaya et al.27 reported a case of PMD in a case series of patients with ectasia and thin corneas who was successfully treated with CXL. Finally, Hafezi et al.5 described a case of effective CXL for postoperative ectasia with underlying forme fruste PMD.
In all cases reported, the standard fluence of 5.4 J/cm² was used, at time and energy settings of 30 minutes and 3 mW/cm². Also, all cases reported that re-epithelialization was uneventful and occurred within 4 days, in the absence of side effects. Spadea²² and Hassan et al.²⁶ reported that they had performed CXL eccentrically by decentering the irradiation zone toward the inferior periphery of the cornea. The question remains as to whether the limbal stem cells tolerate the UV-A irradiation.

**Figure 1.** Re-epithelialization following CXL on 13 mm using standard (5.4 J/cm²) and double-standard fluence (10.8 J/cm²). The erosion was documented immediately after CXL (B, C). At 24 hours (E, F) and 48 hours (H, J) after CXL, re-epithelialization speed was similar for both fluences tested. At 72 hours after CXL, the corneal surface was fully re-epithelialized in standard and double-standard fluence corneas (L, M). The nonirradiated controls showed a similar time to re-epithelialization (A, D, G, K).

**Figure 2.** Light microscopic and immunohistochemical analysis of cornea and limbus. Corneal histology is regular at a fluence of 5.4 J/cm² when irradiating the cornea at a diameter of 7 mm (B) and cornea and limbus at a diameter of 13 mm (C), and similar to the 7-mm (D) and 13-mm (E) irradiations using double-standard fluence (10.8 J/cm²) and controls (A). Cytokeratin 3 (K3) is predominantly expressed in all layers of the corneal epithelium and in the superficial limbal epithelium and its expression pattern is similar in controls (F), at 5.4 J/cm² using 7-mm (G) and 13-mm (H) irradiation, and at 5.4 J/cm² using 7-mm (J) and 13-mm (K) irradiation. The expression pattern of the stem cell marker p63 is also similar for all conditions tested (L–P).
Other diseases of the peripheral cornea in which CXL was applied include Terrien’s marginal degeneration, and rosacea-mediated or trophic peripheral ulcers. In these cases, a decentered irradiation also was performed to cover the area of active disease.\textsuperscript{5,20,21} No limbal stem cell deficiency was reported by the authors.

The corneal epithelium shows a physiological turnover time of 7 to 14 days and also a distinct renewal capacity.\textsuperscript{28,20} Cotsarelis and colleagues\textsuperscript{30} were the first to identify slow-cycling cells in the mouse limbus that might be responsible for this renewal capacity. A number of specific stem cell markers are known today. The cytokeratin K3 represents a corneal-specific marker that is usually expressed by all corneal epithelia and the suprabasal limbal epithelial cells and was first described by Schermer and colleagues.\textsuperscript{31} A marker for limbal epithelial stem cells is the transcription factor p63, which is highly expressed in the basal cell layer, and to a lesser extent in the superficial layers of the limbal epithelial cells. The p63 is not expressed in the corneal epithelium.\textsuperscript{32,33} In our study, we observed an expression pattern similar to untreated controls for all conditions tested (Fig. 2). Accordingly, the speed of epithelial regeneration was similar to controls for both fluences (Fig. 1 and data not shown).

When a sufficient number of stem cells is irreversibly damaged, limbal stem cell deficiency may occur, characterized by a substitution of the corneal epithelium by conjunctival epithelium and leading to corneal opacification.\textsuperscript{34} Stem cells may be damaged by several mechanisms, including chemical burns, inflammatory disease, and light. Short-wavelength UV-B (290–320 nm) and UV-A (320–400 nm) light can induce burns, inflammatory disease, and light. Short-wavelength UV-B may be damaged by several mechanisms, including chemical burn.

For an assessment of the overall risk of potential UV-mediated limbal damage, immediate, midterm, and long-term effects must be considered. Immediate and midterm effects include reduced speed of epithelial regeneration in the early postoperative phase, as well as limbal stem cell deficiency within days to weeks after CXL. The long-term effects include potential UV-A-mediated mutagenic effects. In our study, as well as in all cases reported clinically, epithelial regeneration occurred normally in the absence of signs of limbal stem cell deficiency. With a follow-up of 4 weeks corresponding to two to four times the physiological turnover time of the corneal epithelium,\textsuperscript{38,20} this indicates a regular immediate and midterm response of the limbal stem cells. The overall clinical follow-up of CXL currently is 15 years, and to date, no cases of limbal stem cell deficiency and/or mutagenesis have been reported. On the other hand, even longer follow-ups might be needed to exclude any long-term mutagenic effects.

In conclusion, we show that the regenerative capacity and the structural integrity of the corneal limbus are preserved after a 360-degree UV-A irradiation of the limbus using 5.4 J/cm\textsuperscript{2} (standard CXL) and even 10.8 J/cm\textsuperscript{2} (twice the standard fluence currently used in clinical settings), when compared with the epithelial healing rate of conventional CXL with irradiation of the cornea only.\textsuperscript{25} Also, CXL has been in clinical use since 1999 and, to date, no case of limbal stem cell deficiency or mutagenic effects have been reported. We therefore assume that, in cases in which a sectorial CXL treatment of the corneal periphery is medically mandatory, a partial irradiation of the inferior limbus may be performed in the cornea without harm.

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\textbf{References}


Effect of Standard and High-Fluence CXL


