



Universiteit
Leiden
The Netherlands

Elucidation of the migratory behaviour of the corneal endothelium

Miron, A.

Citation

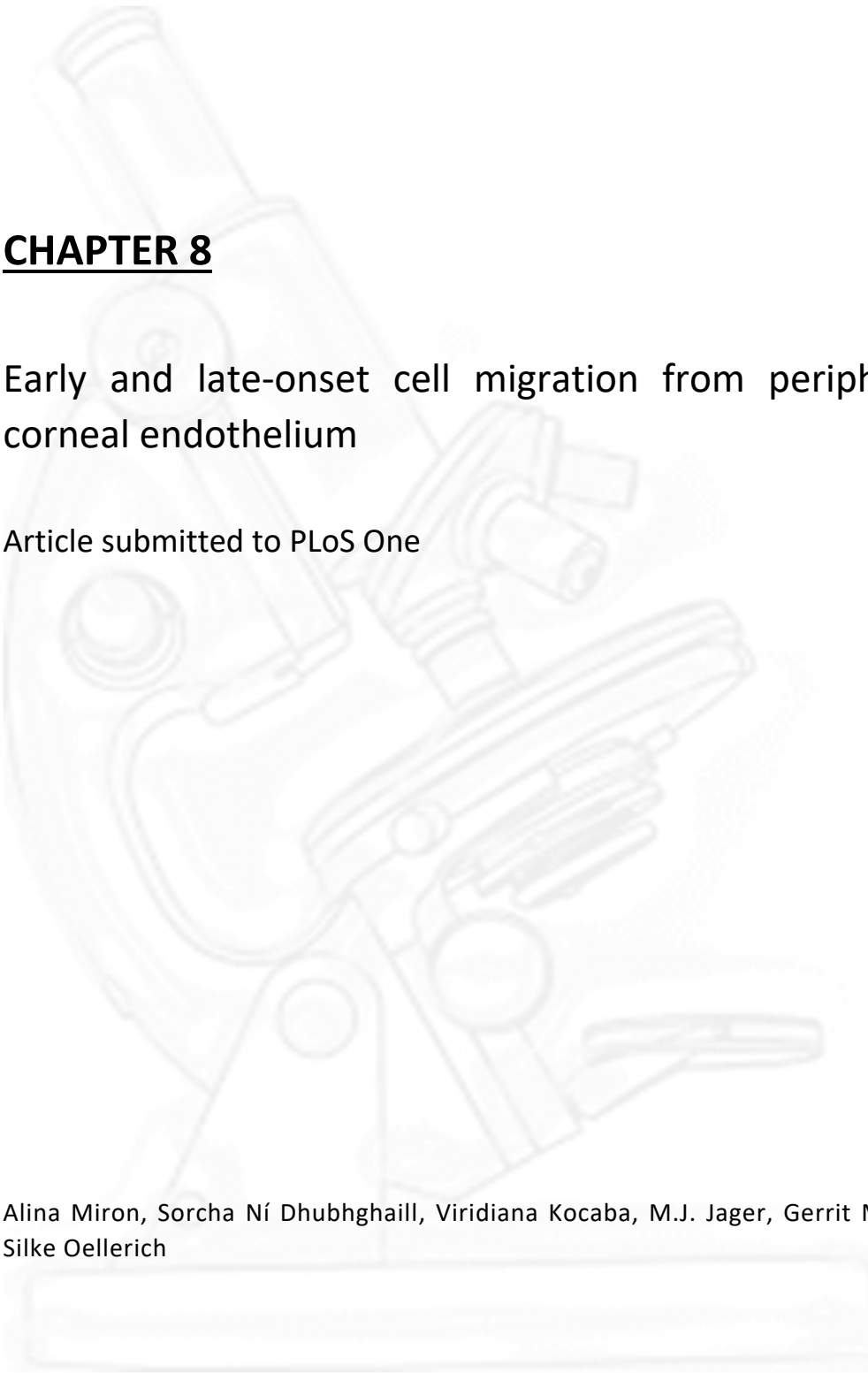
Miron, A. (2023, March 9). *Elucidation of the migratory behaviour of the corneal endothelium*. Retrieved from <https://hdl.handle.net/1887/3570514>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/3570514>

Note: To cite this publication please use the final published version (if applicable).



CHAPTER 8

Early and late-onset cell migration from peripheral corneal endothelium

Article submitted to PLoS One

Alina Miron, Sorchá Ní Dhubhghaill, Viridiana Kocaba, M.J. Jager, Gerrit Melles, Silke Oellerich

ABSTRACT

Aim: To study peripheral corneal endothelial cell migration *in vitro* in the absence and presence of a ROCK-inhibitor.

Materials and Methods: Twenty-one corneal endothelial graft rims, with attached trabecular meshwork (TM), were prepared from Descemet membrane-endothelial cell (DM-EC) sheets by 6.5 mm trepanation. For the initial proof-of-concept, 7 outer graft rims were cultured in a 3D thermo-reversible hydrogel matrix for up to 45 days. To assess the effect of a ROCK-inhibitor, 14 paired outer rims were cultured either with or without ROCK-inhibitor. At the end of culture, tissue was retrieved from the hydrogel matrix and examined for cell viability and expression markers (ZO-1, Na⁺/K⁺ –ATPase, NCAM, glypican-4, and vimentin).

Results: All cultured rims remained viable and displayed either single regions (n=5/21) or collective areas (n=16/21) of cell migration, regardless of the presence or absence of ROCK-inhibition. Migration started, after 4±2 days and continued for at least 29 days. Migrated cells showed a more regular cell morphology when cultured in the presence of a ROCK-inhibitor. In addition, 7 outer rims demonstrated a phenotypically distinct late-onset, but fast-growing cell population emerging from the area close to the limbus. These cells emerged after 3 weeks of culture and appeared less differentiated compared to the other areas of migration. Immunostaining showed that migrated EC maintained the expression patterns of endothelial cell markers.

Conclusion: Using a 3D-culture system, we observed migration of two morphologically distinct cell populations. The first type was triggered by a broken physical barrier, consistent with disruption of contact inhibition. The second, late-onset type showed a higher proliferative capacity though appearing less differentiated. This cell subpopulation appeared to be mediated by stimuli other than the loss of contact inhibition and the presence of ROCK-inhibitor. Further exploration of the differences between these cell types may assist in optimizing regenerative treatment options for endothelial diseases.

INTRODUCTION

The treatment of corneal endothelial failure and dysfunction is transitioning from corneal transplantation towards regenerative therapy.[1–3] Since central corneal endothelial cells are considered terminally differentiated and non-replicative *in vivo*,[4] new therapies that rely on the presence of healthy peripheral endothelial cells, such as Descemet stripping only (DSO), require endothelial migration from the periphery to cover the central area and endothelial cell mitosis through the administration of mitogens.[5–9] During this wound healing process, endothelial cells deposit fibronectin and laminin on the Descemet membrane which supports the required signaling for directed cell migration. Cells undergo cytoskeletal changes during the migration process reflected by cellular enlargement and polymorphism. Since the endothelial cells usually do not replicate *in vivo*, cellular enlargement is needed to cover the wounded areas. It has been suggested, however, that cells from the peripheral corneal endothelium may have proliferative capacity and act as a cell resource for the recovery of corneal endothelium in endothelial injury.[10] When immunostained, peripheral endothelial cells exhibit less differentiation markers than central endothelial cells but express stem cell markers and, sometimes, proliferation markers.[11] Furthermore, these cells were found between the corneal endothelium and the trabecular meshwork (TM) and showed a bipolar, spindle-shaped morphology similar to that of neural crest cells.[12] Recently, progenitor-like cells were discovered to reside within a thin strip of tissue, the transition zone (TZ), initially believed to be a zone depleted of cells.[13,14] These stem cells sequestered in specific niches inside the TZ may respond to corneal wounding to initiate endothelial repair and also contribute to a normal, slow replacement of corneal endothelial cells.

Endothelial cell proliferation and endothelial cell migration can be supported by topical administration of a ROCK-inhibitor, which resulted in improved clinical outcomes after DSO.[15–20]

The purpose of this study is to evaluate *in vitro* peripheral endothelial cell migration from outer corneal graft rims using a thermo-reversible temperature-responsive polymer culture technique both in the absence and presence of a ROCK-inhibitor to gain a better understanding of the process *in vivo*.

MATERIALS AND METHODS

Corneas

Twenty-one human postmortem corneas, which were ineligible for transplantation, but had an intact and viable endothelial cell layer with an average endothelial cell density of 2371 ($\pm$ 313) cells/mm² (from twelve donors (mean age 76 ($\pm$ 5) years; range 68–84 years)) (**Table 1**), were obtained from Amnitrans EyeBank Rotterdam. All donors had previously stated that they had no objection to transplant-related research and the study adhered to the tenets of the Declaration of Helsinki. No specific institutional review board approval was required as under national regulation no approval is required for this research if donors had consented to having the samples used for research purposes (<https://www.ccmo.nl/onderzoekers/aanvullende-eisen-voor-bepaalde-soorten-onderzoek/niet-wmo-onderzoek/onderzoek-met-lichaamsmateriaal>).

Table 1. Demographics of donor corneas.

# Cornea (Donor)	Donor age (years)	Gender	Cause of death	Diabetic status	Sepsis status	Preserv. time before DM-EC sheet prep. (1i) (days)	Preserv. time between 1i and tissue embedding (days)	ECD (cells/mm ²) at cornea preserv.	Rejection reason	DM-EC sheet		
										Cell migration	Outer rim graft	
Proof-of-concept cell migration study												
1 (1 R)	81	M	Circulatory syst.	No	No	14	6	2200	PEQ	CM	SCM	
2 (2 L)	80	M	Circulatory syst.	Yes	No	12	2	2700	Other	CM	SCM	
3 (3 R)	74	M	Circulatory syst.	No	No	16	7	2500	PEQ	n.v.	CM	
4 (4 R)	81	F	Circulatory syst.	No	No	1	2	2500	Virology	n.v.	CM	
5 (4 L)	81	F	Circulatory syst.	No	No	1	2	2500	Virology	CM	CM	
6 (5R)	71	M	Circulatory syst.	No	Yes	12	2	2600	Screening tests	n.v.	CM	
7 (5L)	71	M	Circulatory syst.	No	Yes	12	2	2600	Screening tests	CM	CM	
Mean (±SD)	77 (±5)					11 (±6)	4 (±2)	2514 (±157)				
Paired outer graft rims cell migration study												
										ROCK inhibitor	Cell migration	Late-onset cells
8 (6 R)	84	M	Respiratory sys.	No	Yes	21	2	2300	Other	No	SCM	No
9 (6 L)	84	M	Respiratory sys.	No	Yes	21	2	2300	Other	Yes	CM	No
10 (7R)	80	M	Respiratory sys.	Yes	No	22	2	2400	PEQ	Yes	CM	Yes
11 (7 L)	80	M	Respiratory sys.	Yes	No	22	2	2400	PEQ	No	CM	No
12 (8 R)	77	M	Other	Yes	Yes	24	2	2200	Virology	No	CM	Yes
13 (8 L)	77	M	Other	Yes	Yes	24	2	2100	Virology	Yes	SCM	No
14 (9R)	78	M	Malign.	No	No	4	4	1800	PEQ	No	CM	Yes
15 (9 L)	78	M	Malign	No	No	4	4	1800	PEQ	Yes	CM	Yes
16 (10 R)	68	M	Circulatory syst.	Yes	No	10	3	3000	Virology	Yes	CM	No
17 (10 L)	68	M	Circulatory syst.	Yes	No	10	3	2900	Virology	No	CM	No
18 (11 R)	68	M	Digestive syst.	No	No	15	2	2400	Virology	Yes	CM	Yes
19 (11 L)	68	M	Digestive syst.	No	No	15	2	2400	Virology	No	CM	No
20 (12 R)	75	M	Malign.	No	No	24	2	2300	PEQ	No	CM	Yes
21 (12 L)	75	M	Malign	No	No	24	2	1900	PEQ	Yes	CM	Yes
Mean (±SD)	76 (±6)					17 (±8)	2 (±1)	2320 (±347)				
Mean all grafts (±SD)	76 (±5)					13 (±7)	3 (±2)	2371 (±313)				

CM: collective migration; DM: Descemet membrane; EC: endothelial cells; ECD: endothelial cell density; F: female; L: left donor cornea; M: male; Malign.: malignant; n.v.: not viable; PEQ: Poor Endothelium Quality; Prep.: preparation; Preserv.: preservation; R: right donor cornea; SCM: single cell migration; Screening test: inconclusive blood test; SD: standard deviation; syst.: system; Virology: Hepatitis B positive.

Table 2. Composition of the culture media used in this study.

Culture medium	Growth factors and supplements
Growth factor-depleted DMEM-based medium (M1)	DMEM 15% fetal bovine serum (FBS) 2 mM L-Glutamine (L-Glu)
DMEM based culture medium (M2):	15% fetal bovine serum (FBS) 2 mM L-Glutamine (L-Glu) 2 ng/ml basic fibroblast growth factor (bFGF) 0.3 mM L-Ascorbic acid 2-phosphate (Asc-2P) 10,000 U-ml Penicillin-Streptomycin (Pen/Strep)
ROCK-inhibitor enriched medium (M3):	M2 + 10 μ M ROCK-inhibitor

FBS and bFGF were purchase from ThermoFisher Scientific Europe BV, The Netherlands; DMEM, ROCK-inhibitor, L-Glu and Asc-2P were obtained from Sigma-Aldrich Chemie NV, The Netherlands; Pen/Strep was bought from Carl Roth GmbH, Karlsruhe, Germany

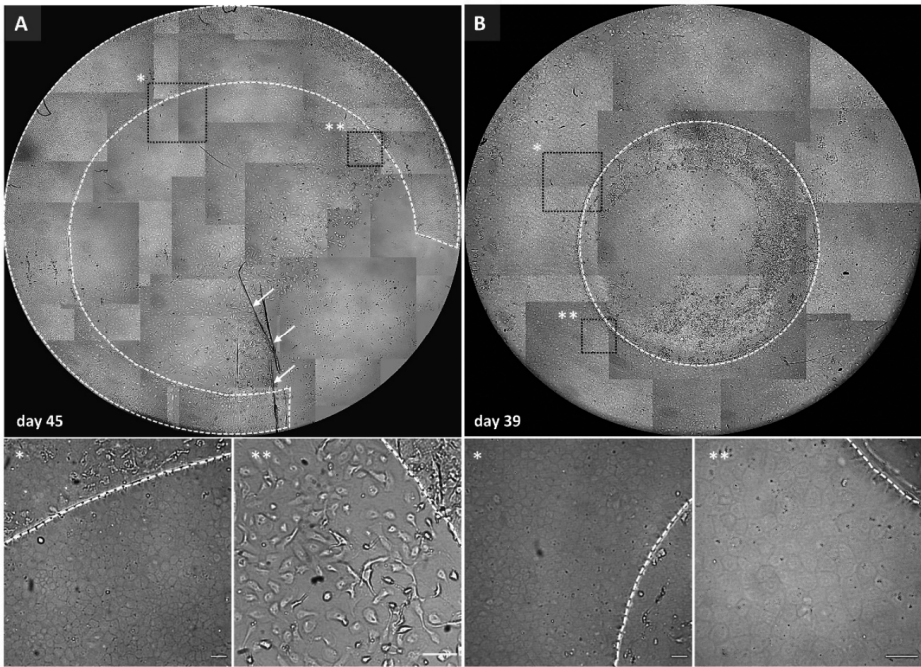


Figure 1| Outer rim and a central graft representation of the proof-of-concept migration study. Collage of light microscopy images (x50) to create an overview of the (A) outer rim cell migration after 45 days in gel culture for which the ring opening was performed in the well using a surgical blade (note the imprints highlighted by the white arrows); the squared areas marked in the overview image display the formations of a cell monolayer free from the DM substrate as a results of collective cellular migration (*) and migration of individual cells (**). (B) 4 mm control graft after 39 days in gel culture showing uniform cell migration from all around the round edges; two higher magnification images marked by * and ** in the graft overview show the cell monolayer formed by the collective spreading of cell cohorts. The dotted line outlines the outer rim (A), control graft (B), and cell monolayer migration edge in the higher magnified images. Scale bar: 100 μ m.

Outer graft rim preparation

Corneoscleral buttons were excised from whole donor globes obtained less than 24 hours postmortem and stored in organ culture medium at 31°C (CorneaMax, Eurobio, Courtaboeuf, France) until graft preparation. The Descemet membrane-endothelial cell (DM-EC) sheets were separated from the stroma by using the standardized “no-touch” peeling technique, as described previously.[21,22] After placing the isolated DM-EC sheets with the trabecular meshwork (TM) still attached on a soft contact lens, the DM-EC sheets were centrally trephined with a 4 mm biopsy punch followed by a second concentric 6.5 mm trepanation to obtain the outer rims. Attachment of the TM prevented the outer rims from scrolling and facilitated further handling. Outer graft rims and 4 mm circular DM-EC sheets were stored separately in growth factor-depleted DMEM-based medium (Table 2, M1) for 2 to 7 days before culture in the thermo-reversible hydrogel matrix (Mebiol Gel, Cosmo Bio, USA).

A thermo-reversible cell culture system not only allows for studying endothelial cell migration but also facilitates tissue retrieval, without enzymatic treatment, by cooling the gel below the sol-gel transition temperature.[23] The preparation of the thermo-reversible hydrogel matrix and embedding protocol have been described in detail in previous publications from our group.[23,24] When embedding the tissue in the hydrogel matrix, the 4 mm circular DM-EC sheets were placed, endothelial-side-up, on glass coverslips and transferred to a 48-well plate.[25] The outer graft rims were transferred to a 24-well plate containing 100 µl Dulbecco’s phosphate-buffered saline (PBS, Sigma-Aldrich Chemie NV, The Netherlands) and positioned endothelial-side-up by grasping the TM with a forceps. The surface was then carefully dried out with cellulose vitreous sponges and the graft rim was carefully cut radially with a surgical blade (Swann-Morton, Sheffield, England) to ensure that the graft rims were mounted completely flat on the surface. Hypotonic trypan blue solution 0.04% (Hippocratech, Rotterdam, The Netherlands) was used to ensure the visibility of both the rims and circular grafts during preparation and unfolding on the solid support. For the initial proof-of-concept experiments, 7 outer graft rims and the corresponding 4 mm circular grafts were embedded separately inside the thermo-reversible polymer solution and evaluated for chemotactic cell ability (Figure 1). The circular grafts acted as the control for cell migration.[23] Following the proof-of-concept, 7 paired outer rims were cultured in the presence or absence of ROCK-inhibitor to assess the effect of ROCK-inhibitor (Y-27632, Sigma-Aldrich Chemie NV, The Netherlands) on the *in vitro* cell migration. The tissue was cultured up to 47 days in a humidified atmosphere at 37°C with 5% CO₂. Medium (Table 2, M2, M3) was refreshed every 2-3 days. Cell morphology and cell migration were examined with an AxioVert.A1 microscope AxioVert.A1 microscope with AxioCam 305 color camera (Zeiss, Oberkochen, Germany). The recovery of the tissue from the hydrogel matrix at the end of the culture period was performed by gradually cooling the gel below the sol-gel transition temperature (<20°C) using low-temperature PBS in the manner previously described.[23]

Immunohistochemistry and cell viability analysis

After the removal of the hydrogel, routine markers such as tight junction protein zonula occludens-1 (ZO-1), vimentin, neural cell adhesion molecule (NCAM), glypican-4 (GPC-4), and sodium-potassium pump (Na⁺/K⁺ –ATPase) were examined for cell characterization. Primary antibodies against vimentin and GPC-4 were obtained from Abcam (Cambridge, United Kingdom) and for Na⁺/K⁺ –ATPase from Sigma-Aldrich Chemie NV (Zwijndrecht, The Netherlands). ZO-1 primary antibody and secondary antibodies were purchased from ThermoFisher Scientific Europe BV (Bleiswijk, The Netherlands). In addition, Calcein-AM (Sigma-Aldrich Chemie NV, The Netherlands) staining was performed to verify cell viability after hydrogel removal. Nuclear cell staining was performed with DNA-specific blue-fluorescent dyes DAPI (Sigma-Aldrich Chemie NV, The Netherlands) and Hoechst (ThermoFisher Scientific Europe BV, The Netherlands). Details of the staining protocols has been described previously.[25]

RESULTS

Cell migration

Proof-of-concept extended culture study

Hydrogel embedding was successful for all 7 outer graft rims and allowed for observation of *in vitro* cell migration from day 2 up to day 47 during which cells migrated either only individually (2/7) or collectively (5/7) (**Figure 1**). For the two graft rings that showed only migration of individual cells, the corresponding 4 mm circular grafts showed collective cell migration (**Supplementary Figure 1A**). Graft ring viability determined by Calcein-AM staining at the end of the culture period showed an overall compromised endothelial cell monolayer integrity with areas almost depleted of cells (**Supplementary Figure 1B**).

ROCK-inhibitor effect on *in vitro* cell migration

Of seven outer graft rim pairs used to test the effect of the ROCK-inhibitor, 5 pairs formed a continuous functional monolayer, as shown by the Calcein-AM and Hoechst staining (**Figure 2**). Mixed cell migration behaviour was observed for the other two pairs. While one graft rim showed collective migration, the contralateral graft rim only displayed single cell migration. For one outer graft rim pair with collective migration initially, cells displayed a coordinated movement that turned into individual cell migration after approximately 17 days of culture. Moreover, cell migration was initiated from edges displaying low viability, whereas it was absent from edges displaying well detected Calcein-AM signal (**Supplement Figure 2A**). A similar migration pattern initiated from mechanically damaged areas was also observed for one outer graft rim cultured in the absence of ROCK-inhibitor (**Supplement Figure 2B**) whereas the contralateral graft rim showed a more uniform distributed migration along the open edges.

Overall, for pairs with collective migration in both graft rims, there was no remarkable difference in terms of the moment when the cell migration started (4 ± 2 days), or the duration, to maintain the direction of motion (44 ± 2 days). The presence of ROCK-inhibitor in the culture medium contributed to a more regular cell morphology of the migrating cells and a migrating cell monolayer without significant formation of any gaps between cells (**Figure 2A, ME vs. 2B, ME**).

Another finding, however, was that seven outer graft rims displayed a phenotypically distinct late-onset (but fast-growing) cell population emerging from the far periphery of the endothelium (**Figure 3**). The late onset migration was seen with both graft rings of 2 pairs, as well as with 3 unpaired graft rings (2 grafts in the presence and 1 in the absence of ROCK-inhibitor), while 2 other pairs did not show the late-onset cells at all. These late-onset cells started to migrate after 3–5 weeks of culture. Presence of ROCK-inhibitor in the growth medium did neither result in a higher percentage of graft rims displaying the late-onset cell population nor did it decrease the time-point when the migration capacity was unlocked (29 ± 8 days with ROCK-inhibitor ($n=4$) vs. 27 ± 3 days without ROCK-inhibitor ($n=3$)). The cells emerged from the intermingled fibrillary area and acquired a more endothelial-like morphology when cultured in the absence of ROCK-inhibitor (**Figure 3D–F, Figure 4A**). These cells became contact inhibited and formed a monolayer of hexagonal cells within 10 ± 4 days (in 4 of 7 cases) and 7 ± 4 days (in 3 of 7 cases) of gel culture in the presence or absence of ROCK-inhibitor, respectively (**Figure 3C, F and Figure 4B**).

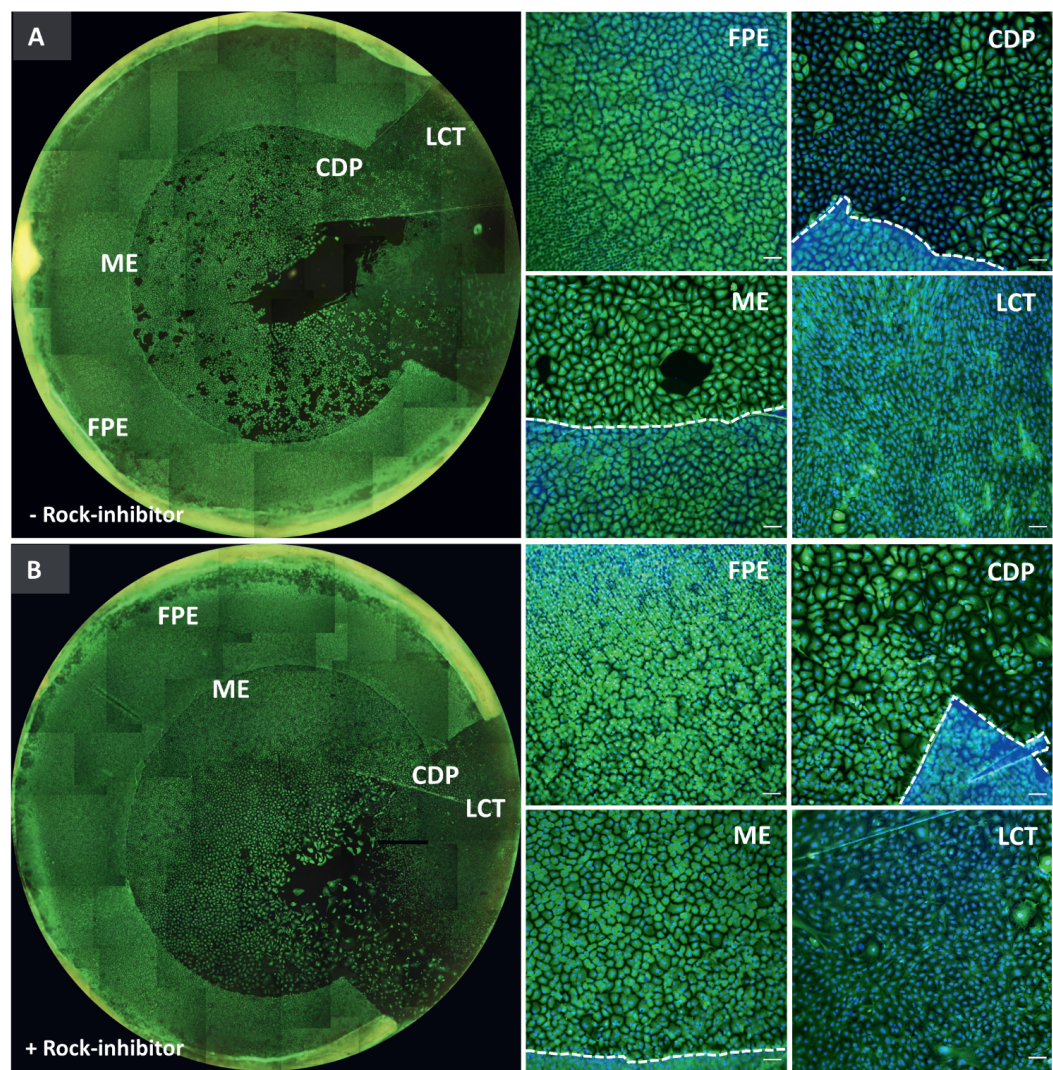


Figure 2 | Calcein-AM and Hoechst staining of representative images of paired outer graft rims cultured in the (A) absence or (B) presence of ROCK-inhibitor. Displayed per culture condition are fluorescence overlay images of Calcein-AM and Hoechst channels representative of far periphery endothelium (FPE), cell monolayer migration edge (ME), cells of different phenotype (CDP) growing around the outer rim opening, and late-onset cell type (LCT) with high proliferative capacity. The dashed lines outline the cell monolayer migration edges. Scale bar: 100 μm .

Outer rim cultured in the absence of Rock-inhibitor

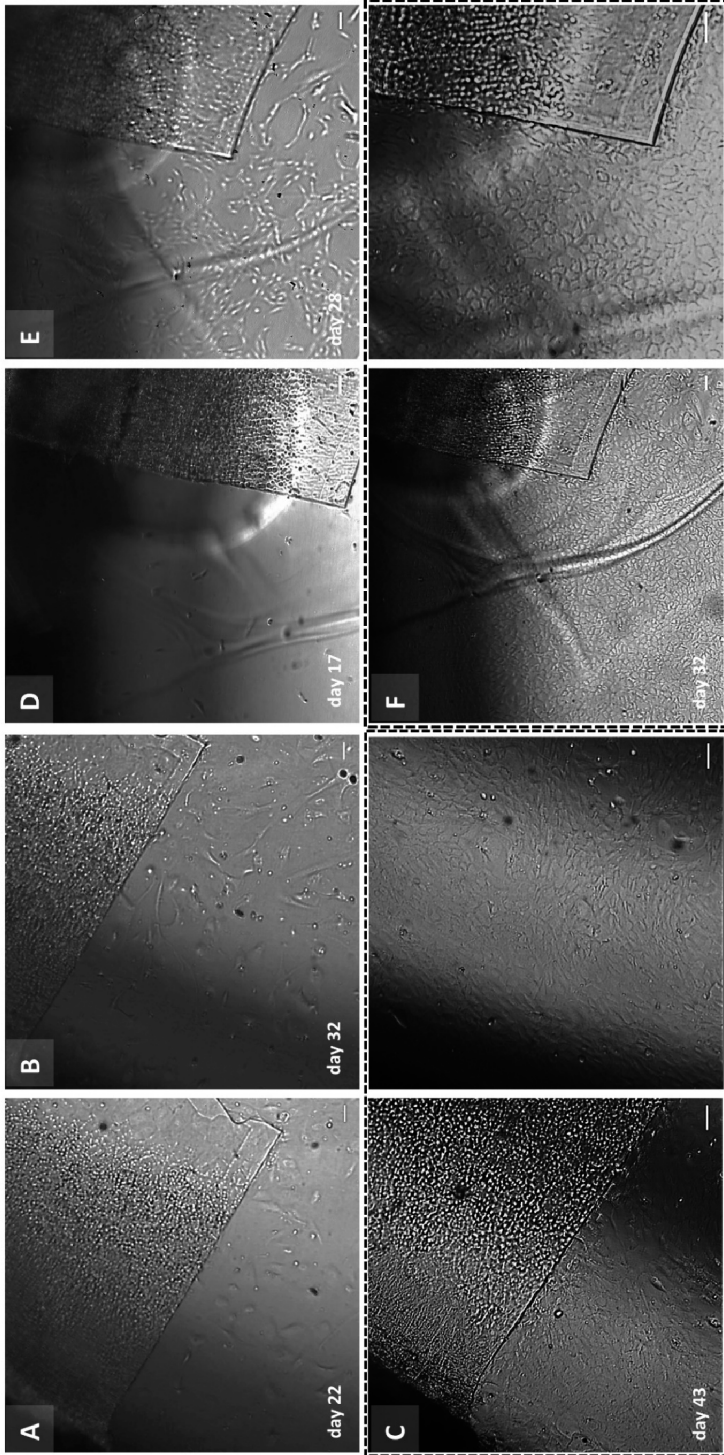


Figure 3 | Representative images of two unpaired outer rims that displayed the late-onset cell type with high proliferative capacity. (A–C) Outer rim cultured in the presence of ROCK-inhibitor and the fast-growing cell type but evident only at day 43. (D–F) Outer rim cultured without ROCK-inhibitor and the fast-growing cell type already visible after 28 days of gel culture. Scale bar: 100 μm.

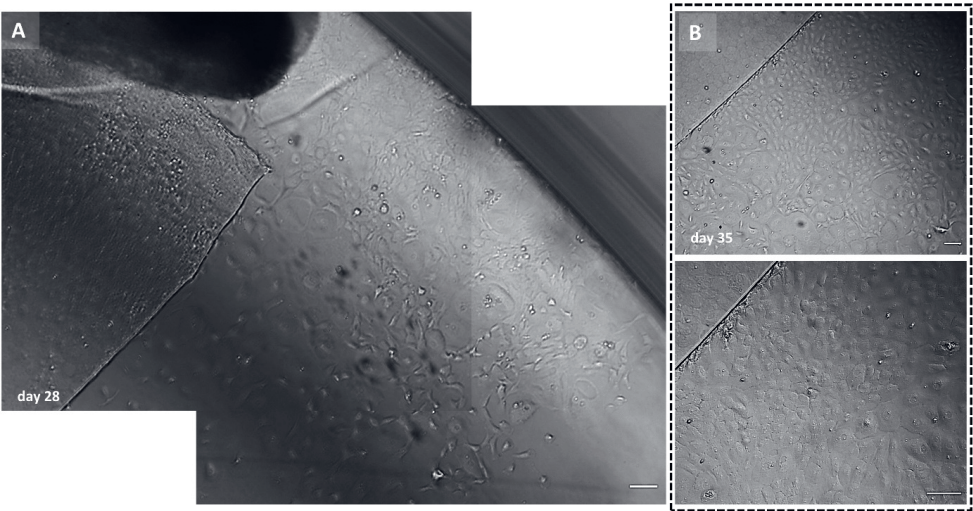


Figure 4| Example images of an outer rim displaying the late-onset cell population without actively targeting the Rho-kinase pathway. (A) cell outgrowth in the far periphery of the endothelium visible after 28 days of gel culture. Note, (i) the different gel embedding plane of the TM that was not physically connected to the endothelium and (ii) the absence of cell migration from the radial cut edge of the outer rim. (B) After 35 days of gel culture, a new cell monolayer of optimal morphology formed around the rim's cut edge. Scale bar: 100 μ m.

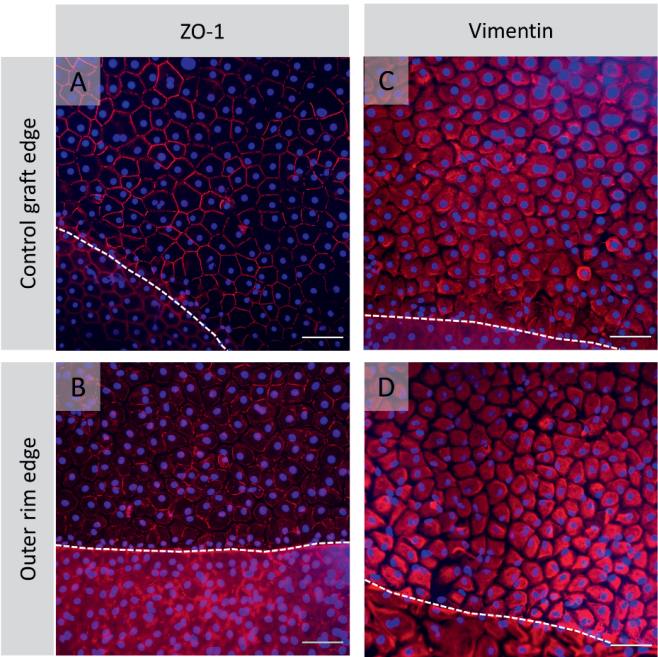


Figure 5| Representative images of structural proteins detected in the cell monolayer with focus on migration edge. Fluorescence microscopy images showing expression of ZO-1 (A, B: red signal) and Vimentin (C, D: red signal)

counterstained with DAPI (blue signal) in the confluent layer of migrating cells: control tissue (4 mm circular graft) (A and C) vs. outer graft rim (B and D). Scale bar: 100 μ m.

Immunohistochemistry

After gel removal, immunohistochemistry analysis showed the typical expression profiles for the endothelial cell markers ZO-1 (**Figure 5A, B**) and Vimentin (**Figure 5C, D**) in the migrated cell monolayer. A weak signal was recorded for the functional marker $\text{Na}^+/\text{K}^+ - \text{ATPase}$, adhesion marker NCAM, and cell surface marker GPC-4 in the cell monolayer formed from the outer graft rim's edge and tissue itself regardless of the culture medium composition (**Table 2**, M2, M3), while the 4 mm circular grafts revealed the formation of a continuous functional monolayer with tightly interconnected cells (**Figure 6**). No visual differences in the immunofluorescent expression patterns were detected between cultured monolayers formed by cell outgrowth from the 4 mm circular grafts with or without ROCK inhibition. Interestingly, cell viability evaluation of the seven outer graft rims with the late-onset cell population showed a heterogenous Calcein-AM signal intensity wherein the lowest signal detection corresponded to the cell population emerged from the far periphery of the endothelium.

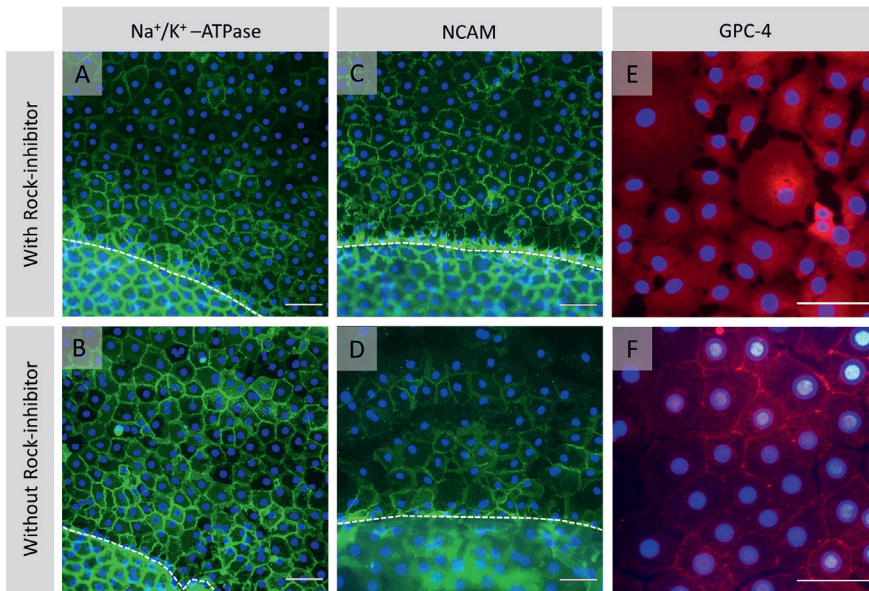


Figure 6 | Immunofluorescence staining of the migrated monolayer from unpaired control grafts. Grafts were cultured with (top line: A, C, E) or without (bottom line: B, D, F) ROCK-inhibitor. Considerable expression of the functional cell marker $\text{Na}^+/\text{K}^+ - \text{ATPase}$ (A, B: green signal), neural cell adhesion molecule NCAM (C, D: green signal), and cell surface proteoglycan GPC-4 (E, F: green signal) was detected in all cultured monolayers irrespective of the culture media composition. Nuclei were stained blue by DAPI. Scale bar: 100 μ m

DISCUSSION

Corneal endothelial explant culture is technically challenging due to the inherent scrolling properties of the tissue, however, using a thermo-reversible hydrogel it is possible to selectively study *in vitro* EC migration from the outer regions of the monolayer with a central opening. Using this approach, we showed that EC migrate

collectively in the majority of outer graft rims with an intact endothelial monolayer. We observed early- and late-onset migration of two morphologically distinct corneal endothelial cell populations. The late-onset type showed a higher proliferative capacity though it appeared to be less differentiated. This cell subpopulation appeared to be mediated by stimuli other than the loss of contact inhibition and ROCK-inhibitor.

When both early- and late-onset migration ceased – on average, 6 weeks vs. 1 week with a lag time of 3–5 weeks, respectively, the cell monolayer became contact inhibited and immunohistochemistry demonstrated the presence of viable cells with tightly packed morphologies. In some other areas, we also noted single cell migration with individual satellite cells branching into the free space, though these were most often seen from areas with mechanical damage. We suspect that the lack of collective migration from the neighboring undamaged endothelial areas may be partly due to inconsistency in flattening the tissue fixed on the support, trapping some regions in the gel during the solidified matrix formation.

Cultures of seven outer rims showed migration of a morphologically distinct, late-onset cell type which appears after 3–5 weeks in culture. These cells arose from the intermingled fibrillary area between the peripheral endothelium and TM. The late-onset cells first adopted a quickly migrating, fibroblast-like morphology (**Figure 3B, E**). Within 10 days of culture, however, the cell migration pattern became more coordinated in which cells acquired an endothelial cell phenotype with a regular morphology (**Figure 3C, F** and **Figure 4B**). Interestingly, cell viability evaluation of outer graft rims with a late-onset cell population showed a heterogeneous Calcein-AM signal intensity (**Figure 2A: ME vs. LCT, B: ME vs. LCT**) where late-onset cells displayed a lower fluorescence signal intensity than the cells that had started earlier with the migration.

The late-onset cells appear to originate from the far peripheral area of the endothelium, a region that has been referred to as a progenitor enriched region (TZ) with the potential to generate mature human corneal EC.[26,27] For the far peripheral endothelium a high mitogenic activity has been reported due to their propensity to sphere formation when cultured on low adhesion surfaces.[28] When spheres were injected into the anterior chamber of rabbit eyes with corneal deficiency, they formed a functional endothelium.[29,30] Zhang et al. demonstrated that TZ cells can proliferate and differentiate into CEC by culturing TZ cells from donor corneal rims.[31] The TZ cells grew from the explant after 20 days of culture, exhibiting initially a rounder polygonal morphology, that become gradually more elongated and fibroblastic during passaging and finally polygonal 2 to 3 passages before senescence. As a general observation, terminal differentiation was identified when the TZ cells spontaneously acquired round and polygonal morphology. While we cannot definitively state that the late onset growth represents TZ cell growth, the timing and end morphology of the cells is highly suggestive.

In our study, the observation of this late-onset cell population was only possible because the outer graft rims had been cut in order to flatten them on the substrate, however, the question is how these cells could be activated *in vivo*. While He et al. hypothesized that cells from the far periphery may have the ability to migrate towards the corneal center along DM grooves,[11] it is yet still unknown whether the TZ/late-onset cells play an active functional role or can be stimulated to be functionally active *in vivo*.

Although endothelial-to-mesenchymal transition (EMT) has been described to occur when CEC are cultured over multiple passages and cells adopted a more elongated morphology,[32] highly proliferative TZ cells first adopt a fibroblast-like morphology and later transform to a polygonal morphology.[31] Previous studies also reported that there is no association of the TZ dimension or proliferative characteristics with donor age, ethnicity, or cell density which is in agreement with our findings that the outer rims showing the late-onset cells were isolated from old donors (68–80 years old) with variable ECD (1800 – 2400 cells/mm²), and preservation time before culture (8–26 days).[26]

Interestingly, the presence of ROCK-inhibitor in the culture medium did not alter the cell outgrowth from the outer graft rims. While it did appear beneficial for maintaining the cell shape and cell-cell adhesion contacts during collective migration, no differences in fluorescence intensity and expression patterns were observed for

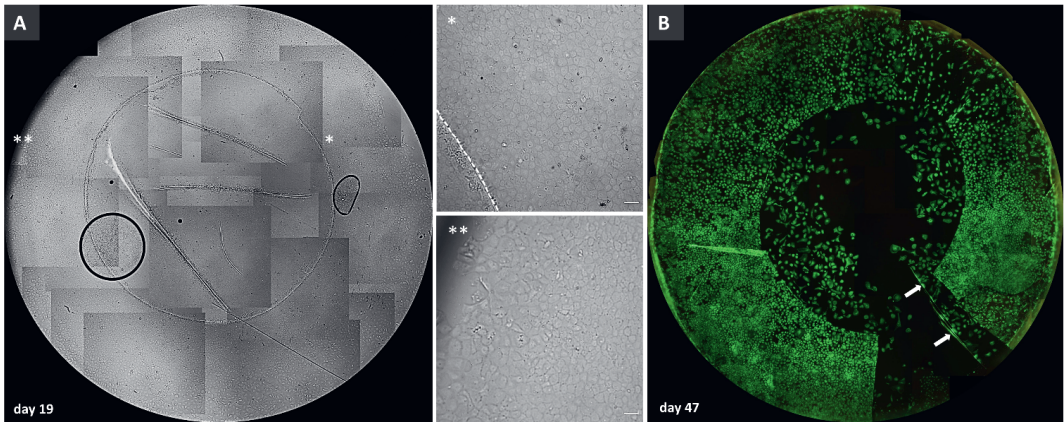
the functional protein marker $\text{Na}^+/\text{K}^+ \text{--ATPase}$ and surface glycoproteins NCAM and GPC-4. Similar observations have been reported in other studies where the authors concluded that ROCK-inhibitors did not induce proliferation or alter the apoptosis of human corneal EC in culture but modulated the cell adhesion properties, cell morphology, and cell junctions by regulating the dynamic rearrangements of the actin cytoskeleton.[33,34] It is possible that the growth factors present in the serum and routinely added to these explant cell cultures already promote cell growth to the point that the effect of a ROCK-inhibitor cannot be detected.

One limitation of our analysis is the small number of outer graft rims used to test whether the ROCK-inhibitor influences the migratory ability of corneal endothelial cells *in vitro* and larger studies are needed to obtain more conclusive results under which conditions ROCK-inhibitor is most effective in stimulating cell migration. A technical limitation was the challenging observation of the late-onset cells, that were located close to the borders of the well-plate, due to an uneven illumination caused by liquid meniscus.

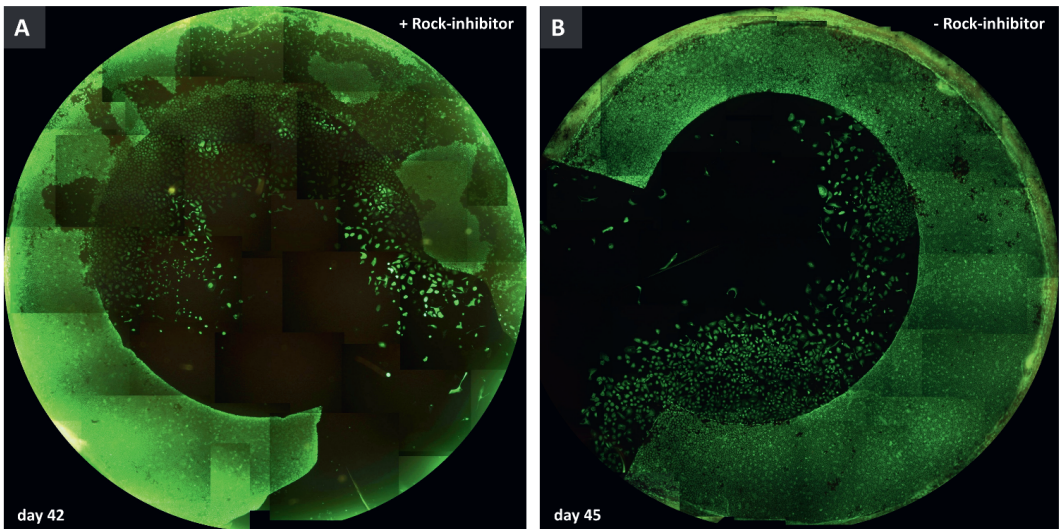
CONCLUSION

In conclusion, we present the findings of selectively studying EC migration from the peripheral cornea by using outer graft rims embedded into a thermo-reversible polymer matrix. In this study, we observed the migration of two morphologically distinct cell populations. The first type was triggered by a broken physical barrier, while the second, late-onset type appeared less differentiated but showed a higher proliferative capacity. It is possible that the activation of the later cell population that displays characteristics of the TZ cells is governed by stimuli other than the loss of contact inhibition and the influence of a ROCK-inhibitor. Understanding the cell migration mechanism from phenotypically distinct regions of the endothelium may assist in optimizing regenerative therapies for endothelial diseases and whether other means of pharmaceutical modulation could further improve the outcomes.

Supporting information



Supplementary Figure 1 | Control graft - outer rim pair showing different cell migration behavior. (A) Light microscopy overview collage (x50) of a control graft cultured for 19 days in 3D gel matrix showing the formation of a continuous monolayer. Higher magnification images from the areas marked by * and ** in the overview image illustrate a contact inhibited cell monolayer. (B) Composite photos (x50) stitched together to create an image panorama of the outer rim stained with Calcein-AM after 47 days of gel culture. Note the imprints (marked by white arrows) left by the surgical blade on the well surface after cutting open the outer rim. Scale bars: 100 μ m.



Supplementary Figure 2 | Fluorescence imaging overviews. Overviews (collage of x50) are shown for two unpaired outer rims stained with Calcein-AM and cultured (A) in the presence or (B) absence of ROCK-inhibitor. Both outer rims showed cells migrating from areas with low viability.

REFERENCES

1. Rolev K, Coussons P, King L, Rajan M. Experimental models of corneal endothelial cell therapy and translational challenges to clinical practice. *Exp Eye Res.* 2019;188:107794. <https://doi.org/10.1016/j.exer.2019.107794> PMID: 31518569
2. Faye PA, Poumeaud F, Chazelas P, Duchesne M, Rassat M, Miressi F, Lia AS, Sturtz F, Robert PY, Favreau F, Benayoun Y. Focus on cell therapy to treat corneal endothelial diseases. *Exp Eye Res.* 2021;204:108462. <https://doi.org/10.1016/j.exer.2021.108462> PMID: 33493477
3. Català P, Thuret G, Skottman H, Mehta JS, Parekh M, Ní Dhubhghaill S, Collin RWJ, Nuijts RMMA, Ferraris S, LaPointe VLS, Dickman MM. Approaches for corneal endothelium regenerative medicine. *Prog Retin Eye Res.* 2022;87:100987. <https://doi.org/10.1016/j.preteyeres.2021.100987> PMID: 34237411
4. Van den Bogerd B, Dhubhghaill SN, Koppen C, Tassignon MJ, Zakaria N. A review of the evidence for *in vivo* corneal endothelial regeneration. *Surv Ophthalmol.* 2018 Mar-Apr;63(2):149-165. <https://doi.org/10.1016/j.survophthal.2017.07.004> PMID: 28782549
5. Vercammen H, Miron A, Oellerich S, Melles GRJ, Ní Dhubhghaill S, Koppen C, Van Den Bogerd B. Corneal endothelial wound healing: understanding the regenerative capacity of the innermost layer of the cornea. *Transl Res.* 2022;S1931-5244(22)00114-1. <https://doi.org/10.1016/j.trsl.2022.05.003> PMID: 35609782
6. Moloney G, Chan UT, Hamilton A, Zahidin AM, Grigg JR, Devasahayam RN. Descemetorhexis for Fuchs' dystrophy. *Can J Ophthalmol.* 2015;50(1):68-72. <https://doi.org/10.1016/j.ijco.2014.10.014> PMID: 25677286
7. Borkar DS, Veldman P, Colby KA. Treatment of Fuchs endothelial dystrophy by Descemet stripping without endothelial keratoplasty. *Cornea.* 2016;35(10):1267-73. <https://doi.org/10.1097/ICO.0000000000000915> PMID: 27310885
8. Iovieno A, Neri A, Soldani AM, Adani C, Fontana L. Descemetorhexis without graft placement for the treatment of Fuchs endothelial dystrophy: preliminary results and review of the literature. *Cornea.* 2017;36(6):637-641. <https://doi.org/10.1097/ICO.0000000000001202> PMID: 28410355
9. Kinoshita S, Colby KA, Kruse FE. A close look at the clinical efficacy of Rho-associated protein kinase inhibitor eye drops for Fuchs endothelial corneal dystrophy. *Cornea.* 2021;40(10):1225-1228. <https://doi.org/10.1097/ICO.0000000000002642> PMID: 34481406
10. Choi SO, Jeon HS, Hyon JY, Oh YJ, Wee WR, Chung TY, et al. Recovery of corneal endothelial cells from periphery after injury. *PLoS One.* 2015;10(9):e0138076. <https://doi.org/10.1371/journal.pone.0138076> PMID: 26378928
11. He Z, Campolmi N, Gain P, Binh Thi BMH, Dumollard JM, Duband S, et al. Revisited microanatomy of the corneal endothelial periphery: new evidence for continuous centripetal migration of endothelial cells in humans. *Stem Cells.* 2012;30(11):2523-34. <https://doi.org/10.1002/stem.1212> PMID: 22949402
12. Hara S, Hayashi R, Soma T, Kageyama T, Duncan T, Tsujikawa M, et al. Identification and potential application of human corneal endothelial progenitor cells. *Stem Cells Dev.* 2014;23(18):2190-201. <https://doi.org/10.1089/scd.2013.0387> PMID: 24588720
13. Yam GHF, Seah X, Yusoff NZBM, Setiawan M, Wahlig S, Htoon HM, et al. Characterization of human transition zone reveals a putative progenitor-enriched niche of corneal endothelium. *Cells.* 2019;8(10):1244. <https://doi.org/10.3390/cells8101244> PMID: 31614883
14. Yu WY, Sheridan C, Grierson I, Mason S, Kearns V, Lo ACYL, et al. Progenitors for the corneal endothelium and trabecular meshwork: a potential source for personalized stem cell therapy in corneal endothelial diseases and glaucoma. *J Biomed Biotechnol.* 2011;4:12743. <https://doi.org/10.1155/2011/412743> PMID: 22187525
15. Moloney G, Petsoglou C, Ball M, Kerdraon Y, Höllhumer R, Spiteri N, et al. Descemetorhexis without grafting for Fuchs endothelial dystrophy-supplementation with topical Ripasudil. *Cornea.* 2017;36(6):642-648. <https://doi.org/10.1097/ICO.0000000000001209> PMID: 28476048

16. Huang MJ, Kane S, Dhaliwal DK. Descemetorhexis without endothelial keratoplasty versus DMEK for treatment of Fuchs endothelial corneal dystrophy. *Cornea*. 2018;37(12):1479-1483. <https://doi.org/10.1097/ICO.0000000000001742> PMID: 30222714
17. Macsai MS, Shiloach M. Use of topical Rho kinase inhibitors in the treatment of Fuchs dystrophy after Descemet stripping only. *Cornea*. 2019;38(5):529-534. <https://doi.org/10.1097/ICO.0000000000001883> PMID: 30720541
18. Artieda JA, Wells M, Devasahayam RN, Moloney G. 5-Year outcomes of Descemet stripping only in Fuchs dystrophy. *Cornea*. 2020;39(8):1048-1051. <https://doi.org/10.1097/ICO.0000000000002270> PMID: 31990847
19. Davies E, Jurkunas U, Pineda R. Pilot Study of corneal clearance with the use of a Rho-kinase inhibitor after descemetorhexis without endothelial keratoplasty for Fuchs endothelial corneal dystrophy. *Cornea*. 2021;40(7):899-902. <https://doi.org/10.1097/ICO.0000000000002691> PMID: 33758139
20. Garcerant D, Hirschschall N, Toalster N, Zhu M, Wen L, Moloney G. Descemet's stripping without endothelial keratoplasty. *Curr Opin Ophthalmol*. 2019;30(4):275-285. <https://doi.org/10.1097/ICU.0000000000000579> PMID: 31033737
21. Lie JT, Birbal R, Ham L, van der Wees J, Melles GRJ. Donor tissue preparation for Descemet membrane endothelial keratoplasty. *J Cataract Refract Surg*. 2008;34(9):1578-83. <https://doi.org/10.1016/j.jcrs.2008.05.036> PMID: 18721723
22. Groeneveld-van Beek EA, Lie JT, van der Wees J, Bruinsma M, Melles GRJ. Standardized 'no-touch' donor tissue preparation for DALK and DMEK: harvesting undamaged anterior and posterior transplants from the same donor cornea. *Acta Ophthalmol*. 2013;91(2):145-50. <https://doi.org/10.1111/j.17553768.2012.02462.x> PMID: 22672202
23. Miron A, Spinozzi D, Lie J, Melles GRJ, Oellerich S, Dhubhghaill SN. Improving endothelial explant tissue culture by novel thermoresponsive cell culture system. *Curr Eye Res*. 2021;46(3):290-293. <https://doi.org/10.1080/02713683.2020.1798468> PMID: 32727221
24. Miron A, Spinozzi D, Dhubhghaill SN, Lie J, Oellerich S, Melles GRJ. *In vitro* endothelial cell migration from limbal edge-modified Quarter-DMEK grafts. *PLoS One*. 2019 ;14(11):e0225462. <https://doi.org/10.1371/journal.pone.0225462> PMID: 31747441
25. Dhubhghaill SN, Miron A, Lie JT, Dapena I, Oellerich S, Melles GRJ. Preclinical testing of small diameter Descemet membrane endothelial keratoplasty grafts to increase tissue availability. *PLoS One*. 2021;16(2):e0246516. <https://doi.org/10.1371/journal.pone.0246516> PMID: 33539395
26. Ming NM, Yam GHY, Soh YQ, Lovatt M, Dhaliwal D, Kocaba V, et al. Regenerative capacity of the corneal transition zone for endothelial cell therapy. *Stem Cell Res Ther*. 2020;11(1):523. <https://doi.org/10.1186/s13287-020-02046-2> PMID: 33276809
27. Wongvisavavit R, Parekh M, Ahmad S, Daniels JT. Challenges in corneal endothelial cell culture. *Regen Med*. 2021;16(9):871-891. <https://doi.org/10.2217/rme-2020-020> PMID: 34380324
28. Yokoo S, Yamagami S, Yanagi Y, Uchida S, Mimura T, Usui T, et al. Human corneal endothelial cell precursors isolated by sphere-forming assay. *Invest Ophthalmol Vis Sci*. 2005;46(5):1626-31. <https://doi.org/10.1167/iovs.04-1263> PMID: 15851561
29. Mimura T, Yamagami S, Yokoo S, Araie M, Amano S. Comparison of rabbit corneal endothelial cell precursors in the central and peripheral cornea. *Invest Ophthalmol Vis Sci*. 2005;46(10):3645-8. <https://doi.org/10.1167/iovs.05-0630> PMID: 16186345
30. Mimura T, Yamagami S, Yokoo S, Yanagi Y, Usui T, Ono K, et al. Sphere therapy for corneal endothelium deficiency in a rabbit model. *Invest Ophthalmol Vis Sci*. 2005;46:3128-3135. <https://doi.org/10.1167/iovs.05-0251> PMID: 16123411
31. Zhang J, Ahmad AM, Ng H, Shi J, McGhee CNJ, Patel DV. Successful culture of human transition zone cells. *Clin Exp Ophthalmol*. 2020;48(5):689-700. <https://doi.org/10.1111/ceo.13756> PMID: 32249477

32. Chen S, Zhu Q, Sun H, Zhang Y, Tighe S, Xu L, et al. Advances in culture, expansion and mechanistic studies of corneal endothelial cells: a systematic review. *J Biomed Sci.* 2019;26(1):2. <https://doi.org/10.1186/s12929-018-0492-7> PMID: 30609919
33. Pipparelli A, Arsenijevic Y, Thuret G, Gain P, Nicolas M, Majo F. ROCK inhibitor enhances adhesion and wound healing of human corneal endothelial cells. *PLoS One.* 2013;8(4):e62095. <https://doi.org/10.1371/journal.pone.0062095> PMID: 23626771
34. Wu Q, Ouyang C, Xie L, Ling Y, Huang T. The ROCK inhibitor, thiazovivin, inhibits human corneal endothelial-to-mesenchymal transition/epithelial-to-mesenchymal transition and increases ionic transporter expression. *Int J Mol Med.* 2017;40(4):1009-1018. <https://doi.org/10.3892/ijmm.2017.3103> PMID: 28849097