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Biomechanical relationships between the corneal endothelium and Descemet's membrane

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Abstract

The posterior face of the cornea consists of the corneal endothelium, a monolayer of cuboidal cells that secrete and attach to Descemet's membrane, an exaggerated basement membrane. Dysfunction of the endothelium compromises the barrier and pump functions of this layer that maintain corneal deturgesence. A large number of corneal endothelial dystrophies feature irregularities in Descemet's membrane, suggesting that cells create and respond to the biophysical signals offered by their underlying matrix. This review provides an overview of the bidirectional relationship between Descemet's membrane and the corneal endothelium. Several experimental methods have characterized a richly topographic and compliant biophysical microenvironment presented by the posterior surface of Descemet's membrane, as well as the ultrastructure and composition of the membrane as it builds during a lifetime. We highlight the signaling pathways involved in the mechanotransduction of biophysical cues that influence cell behavior. We present the specific example of Fuchs' Corneal Endothelial Dystrophy as a condition in which a dysregulated Descemet's membrane may influence the progression of disease. Finally, we discuss some disease models and regenerative strategies that may facilitate improved treatments for corneal dystrophies.

Keywords

Endothelium; Descemet's Membrane; Mechanotransduction; Extracellular Matrix; Topography; Modulus; Fuchs' Corneal Endothelial Dystrophy

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The endothelium is the most posterior layer of the cornea and plays a critical role in maintaining corneal transparency, regulating deturgescence by providing both barrier and transport functions[1]. A monolayer of corneal endothelial cells (CEnCs) maintains a barrier through tight junctions and adherens junctions[1–4]. Osmotic pressure drives water from the anterior segment into the corneal tissues, and the endothelial layer maintains deturgescence through active fluid transport, energetically maintained by Na^+/K^+-ATPases[5–7]. Corneal endothelial cells also produce a specialized basement membrane that forms Descemet's membrane (DM)[8]. Anterior to DM is the stroma, which constitutes the bulk of the cornea[9]. Bowman's layer[10], a specialized acellular extracellular matrix (ECM), separates the stroma from the anterior corneal epithelium in humans, but is absent in all domestic animals[11]. A stratified squamous nonkeratinized epithelium makes up the anterior face of the cornea, with basal columnar cells are anchored to the underlying anterior basement membrane[11]..

It is well-documented that biophysical cues, such as substratum topography and stiffness, intrinsic attributes of all extracellular matrices, profoundly modulate a host of fundamental cell behaviors[12–20]. Corneal cells interact with a rich variety of *in vivo* biophysical stimuli: the stroma and basement membranes present them with a range of stiffnesses and complex topographies[21]. Our laboratory and others have documented that the biophysical attributes of matrices represent ubiquitous and potent cellular stimuli that modulate morphology[22–26], adhesion[27], motility[28,29], proliferation[30], gene expression and regulation[31], and cell differentiation[18,20,32] in a wide array of cell types. These cues also impact how cells respond to soluble signaling molecules and therapeutic agents[17,18,20]. Insights gleaned from research on biophysical stimuli in the cornea inform potential therapies for conditions including corneal wounds[33–35], as well as to tissue-engineered corneal constructs for transplantation[36]. In particular, topographical and mechanical stimuli have been introduced to CEnCs to increase proliferation[26,30], maintain phenotype[37], and produce cell sheets for transplantation[38–40]. Given the evidence supporting the role of mechanical signals in the function of CEnCs, it is surprising that the roles of these signals in homeostasis and pathogenesis have not been explored more thoroughly.

In this review, we present evidence that biophysical interactions must be considered when developing a complete model of the corneal endothelium in health and disease. We begin by describing experimental methods used to explore the biophysical microenvironment of corneal cells, particularly the stiffnesses of the tissues with which these cells interact. Next, we describe the ultrastructure of DM and the variations in the ECM at different stages of an organism's lifespan. We then highlight the signaling pathways that are likely to be involved in transducing mechanical signals from the ECM to the nucleus, thereby influencing cell behavior. To illustrate the reciprocal relationship between ECM and CEnCs, we describe a proposed interaction between DM and endothelial cells, engaging biophysical stimuli in Fuchs' Corneal Endothelial Dystrophy (FCED), a corneal endothelial disease marked by characteristic abnormalities of DM. We then highlight the existing literature on *in vitro* studies of ECM biomolecules produced by CEnCs. We conclude by discussing corneal endothelial regeneration, an active area of research in which a deeper understanding of mechanical cues could have a beneficial impact.

1. Methods for characterizing the biophysical properties of corneal tissues

To investigate biophysical cues and their impact, it is necessary to characterize the mechanical microenvironment that cells experience *in vivo*, and to represent these cues *in vitro*. Tissues are mechanically quantified by measuring the elastic or Young's modulus[41], a property that defines the sample's stiffness or its ability to resist deformation under an applied stress[41]. The elastic moduli of many biological tissues including the cornea have been reported and, interestingly, the reported values for a single tissue type can span several orders of magnitude, largely depending on the method of sample preparation and/or measurement[42] (Table 2). Tensile measurements tend to be of higher magnitude than indentation-based measurements, such as those acquired through atomic force microscopy (AFM) or mechanical interferometry imaging, as the former measures bulk deformations in the tissue (with contributions from the ECM, cells, fibrillar and network-like proteins, and constrained water[42]) whereas the latter methods measure localized deformations on small length scales[42,43].

In thin, heterogeneous tissue samples such as the endothelium or DM, AFM is ideal for measuring the micron-scale deformations that cells and their local ECM environments experience[42,44]. Our lab has extensively used AFM to characterize the stiffness of the distinct layers of the human and rabbit cornea[45–47] (detailed in Table 1), as well as the normal human trabecular meshwork (4.0 ± 2.2 kPa[48]). The properties of the ECM can vary considerably between species[47,49,50], and each layer in the rabbit eye is consistently softer than the corresponding structure in the human eye[47]. For further information, we direct the reader to these reviews on the nuances of stiffness measurements in ocular tissues[42,44] and comprehensive summaries of biomechanical measurements of ocular tissue[51–55].

Topographical characterization of human[21] and canine[56] DMs using scanning electron microscopy (SEM), transmission electron microscopy (TEM), and AFM has documented DM to possess a rich felt-like surface of intertwining fibers, interspersed with elevations and pores. These features, shown in Figure 1[56,57], have sizes on the order of tens of nanometers and fractal dimension of ~2.2[21]. In comparison to the anterior corneal epithelial basement membrane, DM has smaller and more tightly organized features[21,56,5859]. The more compact organization of DM is reflected in its increased stiffness relative to the anterior corneal epithelial basement membrane[45,47]. Cellular basement membrane assembly is influenced by cell-matrix interactions[60] and the biophysical attributes of ECM represent important inputs.

2. The development and ultrastructure of Descemet's Membrane

Like all basement membranes[61], DM is a compact sheet of ECM biomolecules, including proteins and glycosaminoglycans. The composition and ultrastructure of the deposited components vary by developmental stage and pathological state[62], forming distinct layers as they accumulate over a lifetime[63]. Since the mechanical properties of ECM are related to its quantity, its constituent biomolecules, and its degree of crosslinking (through enzymes such as lysyl oxidase and transglutaminases)[64], we hypothesize that these variations would be reflected in differences in the biophysical cues experienced by endothelial cells on DM, as such influences have been observed in other cell types[65]. Since there is no significant

remodeling of DM after deposition, the transverse view serves as an interpretable historical record of development and pathology[63,66].

The thickness of DM ranges from ~3 μm at birth to >10 μm in old age[63]. The anterior region is deposited prenatally, from ~12 weeks after conception, to birth[63]. By 16 weeks after conception, a striated pattern appears in transverse sections[63] and is known as the anterior banded layer (ABL), composed primarily of collagen IV and collagen VIII[67,68]. Ultrastructurally, in the ABL collagen VIII forms several layers of stacked hexagonal lattices[62,68], shown in Figure 2[69–71]. The lattice pattern arises from the molecular structure of collagen VIII as two types of short polypeptide chains, α1 and α2, assemble into homotrimers, then into a tetrahedral intermediate structure, and finally into hexagonal lattices[72] which form characteristic bands (with 100 nm spacing) when stacked[62,73]. In normal human corneas, the two types of collagen VIII polypeptide chains are co-localized as bands within the ABL[74]. This characteristic banded pattern of the ABL is entirely absent in knock-out mutant mice that lack genes for both the α1 and α2 polypeptide chains[75]. These mice have thinner DMs and a lower endothelial cell count suggesting the ABL to be critical to endothelial cell proliferation during development[75].

Near birth, endothelial cell secretion of collagen VIII diminishes as the cells transition from a proliferative to non-proliferative state, but collagen IV secretion continues[8,75,76]. The ECM deposited thereafter lacks the banded pattern and is known as the posterior non-banded layer (PNBL)[62]. The PNBL can be interspersed with small inclusions of fibrillar or banded ECM thought to arise from endothelial cells that transiently lose their postnatal differentiated state[63]. Such anomalous deposits are often found within guttae and Hassel-Henle warts that form in aging corneas[63], suggesting that these abnormal structures form when endothelial cells undergo changes in ECM expression patterns over a lifetime. At this time, to the authors' knowledge, possible differences in the biophysical attributes of the PBL and PNBL remain unexplored. We feel it is likely that both compliance and/or topographic features would differ between these distinct regions of DM and that if such differences are present that they would influence the CEnC phenotype.

3. Biophysical signaling in the corneal endothelium

Since DM is the major source of biophysical stimuli for CEnCs, and since the cells themselves produce the ECM comprising DM, there is a bidirectional relationship between endothelial cells and the ECM they deposit[66,77] (Figure 3). Such a relationship, known as "dynamic reciprocity"[78–80], has been observed in many physiological systems, including the corneal stroma[34]. A detailed understanding of the signaling pathways that underlie these bidirectional relationships may reveal new targets for therapeutic intervention by interrupting the positive feedback loop of dysfunctional ECM – produced under pathological conditions – inducing further pathological cell behavior. The primary pathway impacted by the biophysical attributes of DM is the mechanotransduction pathway, which intersects downstream with the Hippo[81], transforming growth factor β (TGF-β)[82], Wingless/int (Wnt)[83,84], and other signaling pathways[85] that control gene expression. The intersection of critical signaling pathways is presented in Figure 4[86].

Mechanotransduction

Mechanotransduction is the process by which cells sense extracellular mechanical cues, including ECM stiffness, topography, and spatial constraints, and convert them into intracellular biochemical signals leading to cellular responses[14,15]. Transmembrane mechanoreceptors such as integrins and syndecans bind to ECM molecules and detect stresses in the extracellular environment[87]. On the cytoplasmic side, they are linked to the actin cytoskeleton which is critical in generating and transmitting tension throughout the cell, controlling cell morphology and activating downstream signaling pathways[88]. The cell can probe the stiffness of its surroundings by contracting its actin cytoskeleton – a compliant substrate offers less resistance to deformation and induces less stress in the contractile machinery than a stiff one[88]. Mechanical stresses transmitted through mechanoreceptors to the cytoskeleton can alter the assembly dynamics of actin filaments, inducing conformational changes in actin-binding proteins that play regulatory roles further downstream[89]. The cytoskeleton also links to structures in the nucleus, coupling integrin activation directly to nuclear conformational changes and gene transcription activity[90]. It thus plays a central role in enabling extracellular biophysical cues to regulate a variety of cell behaviors, including survival, proliferation, differentiation, migration, adhesion, and polarity[88,91–93]. Integrins additionally regulate the actin cytoskeleton[94] by activating the Rho/ROCK pathway through Src-family kinases and Rho-family GTPases[95] and influence migration, proliferation, and apoptosis[96]. Rho-associated protein kinase (ROCK) has been linked to proliferation[97–101], wound healing processes[33,98,102–104] and the barrier function[1,105–107] in CEnCs[100].

YAP/TAZ and Hippo

The Hippo pathway, critical for management of organ size during development, has been recently shown to intersect with the mechanotransduction pathway. Two transcriptional regulators and key players in the Hippo pathway, Yes-associated protein (YAP) and transcriptional coactivator with PDZ-binding motif (TAZ), were identified by Dupont and colleagues as a necessary relay for conveying mechanotransduction signals to the nucleus for gene regulation[81,108]. In cells adherent to soft substrates or confined to a small area, YAP/TAZ accumulate in the cytoplasm and eventually degrade, whereas when cells are spread or attached to stiff surfaces, YAP/TAZ relocate to the nucleus and induce gene expression[81,109]. The mechanisms behind these localization patterns are unclear, although the regulation of the actin cytoskeleton by the mechanotransduction pathway appears to play key roles[81,108]. For instance, G-protein coupled receptors acting through the actin cytoskeleton inhibit YAP localization in the nucleus by acting on LATS 1/2[110]. The specific roles of YAP/TAZ in the corneal endothelium are currently under investigation: YAP expression in the nucleus and cytoplasm increases in CEnCs at the periphery of the endothelium, coinciding with higher proliferative potential[111]. Additionally, cultured CEnCs have been induced to proliferate by increasing YAP expression[112]. Because YAP and TAZ are targets and effectors of numerous cell-signaling pathways, including Hippo, TGF-β, Akt, and both canonical and non-canonical Wnt pathways[86,113,114], they can orchestrate the influence of mechanical cues on a wide range of cell behaviors, including epithelial-mesenchymal transition[115].

TGF-β

Members of the TGF-β family are cytokines that are generally inactive in the ECM until released upon injury or mechanical stress, and then bind to membrane receptors[116]. This initiates downstream signaling, activating several types of Smad proteins that form a complex, translocate to the nucleus, and promote transcription.[116] In CEnCs and other cell types, they induce the synthesis, remodeling, and degradation of ECM proteins[117], and trigger the transdifferentiation activity known as epithelial-mesenchymal transition (EMT)[118–120], which is a feature of FECD[121–124]. Changes in matrix protein expression are likely to alter the biophysical properties of the secreted ECM, invoking a mechanotransduction response within the cell. Additionally, the Smad protein complex interacts with YAP/TAZ in some cells to evoke an enhanced fibrotic or metastatic response[116,125]. Through these mechanisms, the TGF-β pathway may impact the dynamic reciprocity between CEnCs and the ECM.

AKT

The Akt pathway promotes survival and growth in response to extracellular signals, including cytokines, hormones, and ECM interactions. It is initiated when the cell surface receptor phosphatidylinositol 3-kinase (PI3K) is activated. Akt, a serine/threonine kinase, is then activated and initiates downstream processes[126]. In CEnCs, fibroblast growth factor 2 (FGF-2) initiates the Akt pathway and promotes proliferation[127]. Furthermore, Akt-induced proliferation in CEnCs is inhibited by TGF-β2 via the latter's transcription products[127]. The Akt pathway also intersects with the downstream relays of the mechanotransduction pathway: Akt interacts with YAP/TAZ and localizes them in the cytoplasm while limiting their degradation[128]. Through these interactions, the Akt pathway has multiple impacts on dynamic reciprocity.

Wnt

The Wnt pathway plays key roles in development, homeostasis, disease, and mechanotransduction. In the canonical pathway, Wnt ligands bind to membrane receptors, initiating a downstream signaling cascade that stabilizes intracellular β-catenin, saving it from degradation and allowing it to regulate transcription in the nucleus[116]. If sufficient Wnt antagonists are present, the pathway is inhibited and cytoplasmic β-catenin is marked for degradation, limiting its transcriptional activity[116]. However, β-catenin can be rescued from degradation by association with YAP/TAZ. The Wnt pathway is thereby influenced by downstream relays of mechanotransduction. A few more interactions are worth noting: In the corneal endothelium, matrix metalloproteinase inhibitors can reverse EMT through inhibiting the Wnt pathway, thereby linking pathological cell behavior to ECM remodelling[129]. A non-canonical (β-catenin independent) Wnt pathway regulates the cytoskeleton via Rho GTPases[130]. Rho GTPases activated through PI3K are linked to increased EMT in CEnCs[131]. This EMT increase occurs when CEnCs are induced to proliferation through disruption of their junctions and the addition of FGF-2[131]. However, Wnt activation can be bypassed by silencing nuclear p150 catenin to activate the Rho pathway[132]. All these interactions provide points at which the Wnt pathway can have an influence on the dynamic reciprocity between the endothelium and DM.

The signaling pathways described above converge on two cellular responses in particular: proliferation and EMT-induced ECM expression. Changes in the ECM, in turn, influence the cell mechanically, creating a closed loop of influence in which abnormal matrix can trigger the expression of more abnormal matrix. Both cellular responses are relevant to the corneal endothelium in health and disease.

4. Dysfunction of the corneal endothelium

Primary corneal diseases are widespread and represent the third leading cause of blindness[70,133]. Diseases of the corneal endothelium are especially burdensome. While the CEnCs of some species, such as rabbits and cows, retain some proliferative capabilities throughout life[134], human CEnCs are especially notable for their low proliferation rate, which is insufficient to replace cells lost through age, trauma, or disease[135]. The remaining cells migrate and enlarge to maintain the intact monolayer[136] leading to subsequent cellular polymegathism and pleomorphism in the endothelium[137]. If the endothelial cells cannot maintain an intact monolayer, their barrier as well as pump functions are disrupted leading to stromal edema and a progressive decrease in visual acuity[70]. The endothelium can degenerate because of primary corneal dystrophies, or secondary to other disturbances to the eye such as glaucoma[138], uveitis[139], or intraocular surgery[140]. The likelihood of secondary changes such as bullous keratopathy are increased if the endothelium has pre-existing signs of vulnerability, and candidates for anterior segment surgery should be screened for low endothelial cell counts[141–143]. The health of CEnCs is closely linked to the state of DM to which they adhere. Many dystrophies are associated with the production of abnormal ECM or amyloid deposits that are likely to change the topography and modulus of the membrane[144,145], suggesting that biophysical interactions with cells may have an impact on a wide range of corneal diseases. Here, we provide a brief introduction of the biophysical properties associated with corneal endothelial dystrophies.

4.1 Fuchs' Corneal Endothelial Dystrophy

Fuchs' Corneal Endothelial Dystrophy (FCED) is the most common corneal endothelial dystrophy in the United States[70]. Clinically, FCED manifests as a thickened and multi-layered DM, with the presence of corneal guttae, corneal edema and deterioration of vision[74].

It occurs in two forms, a late-onset variant and a rarer early-onset variant[146]. In addition to their clinical presentation of thickened DM and gutta formation, the two forms of FCED involve Collagen VIII in distinct ways. Fuchs' dystrophy has been linked to mutations in genes with a variety of functions, begging the question of how a diverse set of genes lead to the common phenotype of abnormal ECM production. Here, we discuss the alterations of ultrastructure and composition of DM in FCED, discuss the associated genetic anomalies that may alter the ECM composition and organization, and consider how these changes may impact intrinsic biophysical attributes, cell function and survival.

Ultrastructural studies of DM in FCED patients reveal a characteristic pattern. Descemet's membrane of FCED patients' corneas is thicker than that of age-matched normal corneas, although the PNBL is thinner. In late-onset FCED, the ABL is slightly thicker than normal.

There is a gradual transition from the PNBL to a posterior collagenous layer (PCL) interspersed with banded patterns termed “widespaced collagens” similar to that of the ABL[62,66,147]. Some corneas, particularly those with pronounced edema, also have a loose “fibrillar layer” between the banded PCL and endothelial cells[147]. The arrangement of wide-spaced, amorphous, and fibrillar ECM is increasingly irregular and distorted toward the posterior of the cornea[147]. The guttae that appear on the posterior DM in FCED are also composed of ECM similar to the PCL[147]. In early-onset FCED, the ABL is notably thicker than normal[74]. It is followed by a PNBL similar to that in late-onset FCED, and an internal collagenous layer (ICL) reminiscent of the PCL in late-onset FCED[74]. Posterior to this is a very thick, collagen VIII-rich posterior striated layer, which does not occur in late-onset FCED[74]. Guttae are smaller than in late-onset FCED and buried within other deposited ECM material[148].

Corneal endothelial cells have the latent ability to synthesize a larger set of ECM protein types than they normally produce, and diseases may arise when regulation of protein expression is dysfunctional[149]. In late-onset FCED, there is increased deposition of collagen IV, laminin, fibronectin, and several other ECM components in the posterior of DM[74,150].

While Collagen VIII is normally found only in the ABL of DM, appearing as arrayed domains of the α1 and α2 chains[74], this arrangement of Collagen VIII is disrupted in FCED. Collagen VIII are also expressed in the PCL, indicating that its production is resumed after cessation in infancy[62]. Interestingly, Collagen VIII plays a different but central role in early-onset FCED also. This condition is associated with mutations in COL8A2. A few familial pedigrees and sporadic individuals have been identified that carry missense mutations in COL8A2 (either Q455K, Q455V, or L450W[148,151]). In patients with the L450W mutation, intracellular and extracellular collagen VIII accumulation correlated with the severity of the disease[152]. Corneas of patients with early-onset FCED, as well as corneas in mouse models with COL8A2 knock-in mutations, have a thickened DM, guttae, changes in endothelial cell morphology, and cell loss, supporting the idea that mutations in Collagen VIII can produce signs of FCED independently of other mutations[153,154].

It is as yet unclear what mechanisms trigger changes from one type of ECM composition to another, and why the various layers in normal and pathogenic DMs appear as they do. However, we can speculate on how these ECM alterations modify the biophysical environment experienced by cells. For instance, since point mutations can affect protein folding, it is likely that mutant COL8A2 in early-onset FCED leads to the expression of collagen VIII chains that do not assemble into the same macromolecular structures as normal chains do[155]. This could alter the biophysical properties of DM, thereby triggering expression changes within the cell.

In addition to the COL8A2 mutations in early-onset FCED, several genetic mutations have been associated with FCED, and these are comprehensively reviewed in the literature[70,156]. The affected genes TCF4 and TCF8 express the transcription factors E2-2 and ZEB1 respectively, which are known to promote EMT[157,158]. TCF8 also alters the expression of Collagen IV, which is abundant in DM[159]. Changes in these key functions of ZEB1 may contribute to abnormal ECM deposition. Several mutations, in COL8A2[152], SLC4A11[160],

and LOXHD1[161], cause cytoplasmic accumulation of proteins. These may induce gutta formation through a mechanism involving the accumulation of proteins in the endoplasmic reticulum, and subsequent unfolded protein response, that has been proposed by Son, et al[162].

In FCED, the PCL is less stiff than the PNBL of the normal DM, and this may be due to alterations in the composition, assembly patterns, and hydration content of the matrix[163,164]. The composition of the ECM can greatly influence the modulus[165]. The heterogeneity of the PCL ultrastructure may interrupt the packing structure of ECM biomolecules, changing the PCL density and modulus relative to the normal PNBL[166,167]. As the DM is normally defined by the network structure of collagen IV, the presence of a fibrillar layer is also likely to change the surface attributes with which endothelial cells interact[168]. Wide-spaced collagens also alter the topography of the DM surface, as revealed by AFM imaging[163].

As guttae are physical structures growing on DM, they exert particular biophysical cues on CECs. The guttae appear as round, flat-topped growths that are 5 to 50 μm in diameter[163] and up to 20 μm in height[169]. The height of topographic features has been shown to impact cell behaviors though at scales significantly smaller than guttae[170]. A preliminary report suggests that the micron-scale dimensions of guttae can impact CEnC behaviors including migratory behavior and monolayer formation *in* vitro [152]. In histopathological sections of FCED corneas, the cells exhibit a spread morphology over guttae with cell bodies displaced laterally to the guttae stems but with sections of cell membrane intact over gutta apices[171]. This displacement is sufficient to distort the cells and apply tensile forces to their actin cytoskeletons. Such mechanical stretch has been associated with EMT in other cell types[172], and this distortion of CEnCs may induce or contribute in part to the EMT-like behavior seen in FCED. With limited space for organelles in the stretched areas and for Na^+/K^+-ATPase on the diminished lateral membranes, the pump function of the corneal endothelium may be quite diminished[171]. However the barrier function of the endothelium is retained as cells remain adherent to one another until late in disease progression[171].

For a complete understanding of the role of biophysical cues in pathogenesis of FCED, we need to fully characterize the biophysical cues presented by DM in FCED, understand how the signaling pathways initiated by mechanotransduction determine the downstream impact on cell health, gutta formation and ECM protein expression. While there are several animal models for FCED, including transgenic mice[153,154] and Boston terriers[173], the biophysical attributes of DM and endothelium in these species remains uncharacterized. Given the challenges in observing the early development of FCED, *in vitro* cell models of the disease could help us fill these knowledge gaps.

4.2 Other endothelial disorders

Posterior Polymorphous Corneal Dystrophy is a rare, slowly progressive or non-progressive condition that develops during the first decade of life but is often asymptomatic.[174] It is characterized by a multilamellar DM with vesicle- and band-like lesions and focal nodular excrescences[70,175]. Congenital hereditary endothelial corneal dystrophy presents as a cloudiness or opacification and edema of the cornea that is present at birth or develops in infancy[70]. Disruption of collagen fibrils occurs in the stroma as well as the production of a

fibrous collagen layer posterior to DM[70]. Subepithelial amyloid deposits have been reported in several cases[156,176–179]. X-linked corneal endothelial dystrophy was recently discovered in 60 members of a single family[180]. The corneas developed opacifications including congenital cloudiness, subepithelial band keratopathy, and endothelial pits[180]. Examination of one cornea revealed an irregularly thickened DM, consisting of an abnormal ABL, an abnormal posterior banded zone of varying ultrastructure and thickness, and an absent PNBL[180]. Iridocorneal endothelial syndrome (ICE) is a group of related corneal disorders in which endothelial cells migrate onto the iris and block the drainage angle, leading to iris atrophy and glaucoma[181]. In a study of 27 ICE affected corneas, the majority possessed DMs with a posterior layer of microfibrils embedded in an amorphous matrix. In several others, there were no banded collagenous layers either anterior or posterior to the non-banded layer[182]. The commonality in features across several corneas suggests these patterns are specific to the mechanisms of ICE[182].

Although the mechanical, topographical, and biochemical properties of DM in these diseases have not been well characterized, we note a recurring incidence of abnormal ultrastructure and the appearance of lesions, excrescences and craters in DM[70,175,180,181,183]. These features very likely offer abnormal topographical and mechanical cues to endothelial cells growing on and interacting with the membrane, which could trigger pathological processes such as EMT[184] or apoptosis[185]. While it is yet unclear whether these biophysical abnormalities in DM are responsible for, or merely coincide with, endothelial cell dysfunction and premature degeneration, there are other instances in the biomedical literature of dysregulated extracellular matrix causing pathological behavior including fibrosis, atherosclerosis and tumorigenesis[186,187]. Furthermore, our lab has demonstrated that changes to substratum compliance and topography can promote the transformation of corneal fibroblasts to myofibroblasts[18,20], leading us to hypothesize that the biophysical characteristics of DM impact endothelial cell morphology and function.

5. *In vitro* studies of ECM in corneal endothelial cells

To delineate the mechanisms of corneal endothelial dystrophies and identify efficacious treatments, it is critical to establish *in vitro* disease models using cell culture. A complete description of mechanism needs to capture the bidirectional interactions between cells and ECM, and characterize ECM expression changes in the presence of mutations, stress, EMT, and disease states. While some studies of CECs have measured ECM gene and protein expression changes, the resulting matrix has rarely been characterized.

The major protein component of the ECM expressed by CEnCs is collagen[188], predominantly collagens IV, VIII, XII, and XIII[150]. The production of a matrix, similar to DM in appearance and collagen content, by rabbit CEnCs was first reported in 1974[189]. Over the next two decades, studies showed that the content of the ECM produced by CEnCs could be modulated by treating the cell culture with growth factors, such as FGF-2[190] and TGF-β[117], that also play a role in EMT[191]. Cells cultured at suboptimal conditions, e.g. passaged repeatedly at subconfluence in the absence of FGF-2, eventually shift to a higher production of collagen I[188]. One study demonstrated that ECM production by CEnCs in response to TGF-β depends on the expression levels of the EMT-inducers Snail1 and ZEB1,

which tend to be elevated in FCED-derived cells[121]. Immortalized cells derived from normal and FCED-affected endothelia were cultured to deposit ECM on polyester membranes, and transmission electron microscopy was used to quantify and compare the thicknesses of the deposited matrices. In the FCED-derived cells, expression of collagen I, collagen IV, and fibronectin was elevated, and the ultrastructure revealed more fibrillar ECM compared to in normal phenotype cells.

A key *in vitro* strategy to understanding the role of ECM in disease and mechanotransduction is to culture cells on ECM substrates with differing biophysical attributes and investigate their responses. An early study culturing normal CEnCs for a week on FCED-derived DM did not show abnormalities in morphology or monolayer formation, although the study was limited in time and did not investigate cell function[192]. Interestingly, cells cultured on pseudophakic bullous keratopathy-derived membranes adopted an abnormal non-confluent stellate form, indicating that this rapid-onset condition disrupts DM and modulates cell growth more acutely[192]. CEnCs have also been plated on ECM-coated tissue culture dishes[193] and soft substrates[37] to assess which surfaces best promote the normal corneal endothelial phenotype. Synthetic substrates that are biomimetic of DM stiffness have also been developed, particularly to enhance proliferation and monolayer stability in artificial corneal grafts[37,194]. Another approach to study cell response to ECM is to deposit a matrix from cells in a long-term culture, decellularize the matrix, and then use the matrix as a substrate for a *de novo* cell culture[195] but this approach has not been applied to CEnCs to the authors' knowledge.

The development of *in vitro* models that mimic both homeostatic and disease states would better enable us to recapitulate the abnormal ECM signals in corneal dystrophies, assess their impact on cell fate, and characterize the resultant expressed matrix biomolecules.

6. Impact of biophysical cues on regenerative treatments

The successful *in vitro* culture of CEnCs is a prerequisite for novel regenerative treatments. Presently, the most common treatment for corneal endothelial dystrophies is transplantation of the full-thickness cornea or DM with associated CenCs, but a global shortage of available donors has driven the development of cell replacement therapy approaches[196] and synthetic corneal endothelium grafts[196,197]. Cell replacement therapy involves the culture and expansion of CEnCs *in vitro*, and subsequent transplantation into the eye without a carrier material. Successful cultures have been established by overcoming proliferative arrest of CECs through the disruption of junctions[198], and treatment with small molecules (e.g. Rho-kinase inhibitors)[104,112] and growth factors (e.g. FGF-2)[188,199]. Furthermore, corneal endothelial precursor cells from the peripheral cornea have a higher than average proliferative capacity and corneal endothelial stem cells are located in a sequestered niche at the limbus between the endothelium and trabecular meshwork[200]. Cultures established with the endothelial stem cells have been delivered into animal models of bullous keratopathy, where they adhered to DM and enhanced corneal clarity[201].

For ease of delivery, it may be necessary to culture corneal endothelial cells on a carrier before implanting the construct as an artificial graft. Grafts have been prepared by culturing

endothelial cells on native tissue such as decellularized DMs[202], amniotic membranes[203], and lens capsules[204]. Carriers of cultured cells have also been synthesized with biological materials such as collagen I[205,206], silk fibroin[207], and chitosan[208]. ECM-based coatings are frequently applied to the carriers to enhance cell function [193,209–211]. Blended biomaterials combine the desired properties of their components to produce surfaces that have clarity, biocompatibility, and mechanical strength[212,213]. Another desired trait, the non-destructive detachment of intact endothelial monolayers, has been achieved through the development of thermoresponsive[38,214,215] and biodegradable[208,212,214,216] substrates.

These artificial grafts and carriers have not yet recapitulated the functionality of the native cornea to a clinically-relevant degree: cell density and quality do not match the native endothelium, the Na^+/K^+-ATPase pump function is 75–95% that of normal human donor corneas, and the corneas engrafted with cellularized matrices eventually lose their transparency[197]. Introducing optimized biophysical cues into matrix design parameters may alleviate many challenges in recapitulating corneal function in these artificial constructs by improving functional protein expression. Endothelial cell morphology is dramatically improved on substrates imitating the stiffness of normal DM in comparison to softer or stiffer substrates[37]. Similarly, cells grown on substrates presenting biomimetic topographic cues also exhibited differential protein expression. Immortalized human CEnCs grown on nanopillars, micropillars, and microwells displayed varied levels of the ZO-1 and Na^+/K^+-ATPase proteins, with the highest expression on substrates that minimized the cells' surface area[26].

The mechanical properties of carrier materials have been improved to produce substrates that are strong enough to survive cell culture and handling, but the provision of biophysical cues has not been adequately explored and this remains an understudied area. Incorporation of these features into the design of carrier substrates may be critical to developing grafts with long-term success.

Conclusion

CEnCs, and the matrix that they secrete to produce the DM, have a bidirectional relationship. Corneal endothelial health relies on a normal and intact DM, and in turn healthy endothelial cells are necessary for the production of a normal extracellular matrix. This relationship in endothelial health and disease has been understudied and it critical that we consider the role of biophysical signals provided by the ECM. Fortunately, there are many tools available to characterize the cells' mechanical microenvironment and recapitulate it *in vitro* to provide a better model of what the corneal endothelium senses *in vivo*. The insights gleaned from investigating these interactions will expand our understanding of the pathogenesis of corneal endothelial dystrophies, and lead to improved outcomes for treatments.

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Abbreviations

CEnC	corneal endothelial cells
ECM	extracellular matrix
DM	Descemet's membrane
FCED	Fuchs' corneal endothelial dystrophy
AFM	atomic force microscopy
SEM	scanning electron microscopy
TEM	transmission electron microscopy
ABL	anterior banded layer
PNBL	posterior non-banded layer
TGF-β	transforming growth factor β
Wnt	Wingless/int
YAP	Yes-associated protein
TAZ	transcriptional coactivator with PDZ-binding motif
EMT	epithelial-mesenchymal transition
PI3K	Phosphoinositide 3-kinase
FGF-2	fibroblastic growth factor-2
PCL	posterior collagenous layer
ICE	Iridocorneal endothelial syndrome

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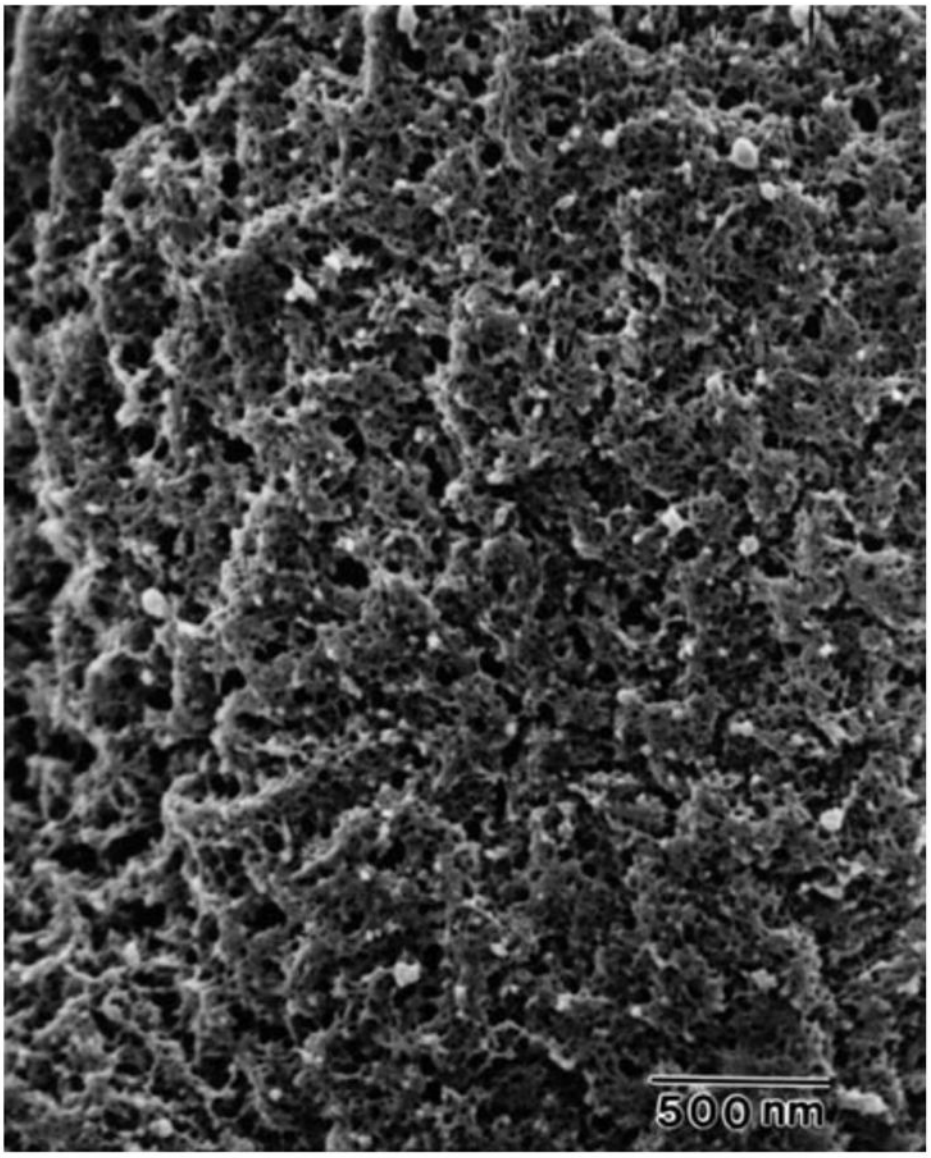
Research Highlights

- Descemet's membrane presents biophysical cues to endothelial cells
- Mechanotransduction influences cell behavior such as matrix production
- In dynamic reciprocity, biophysical cues and matrix production modulate each other
- Understanding these relationships helps develop models for corneal dystrophies

1(a)



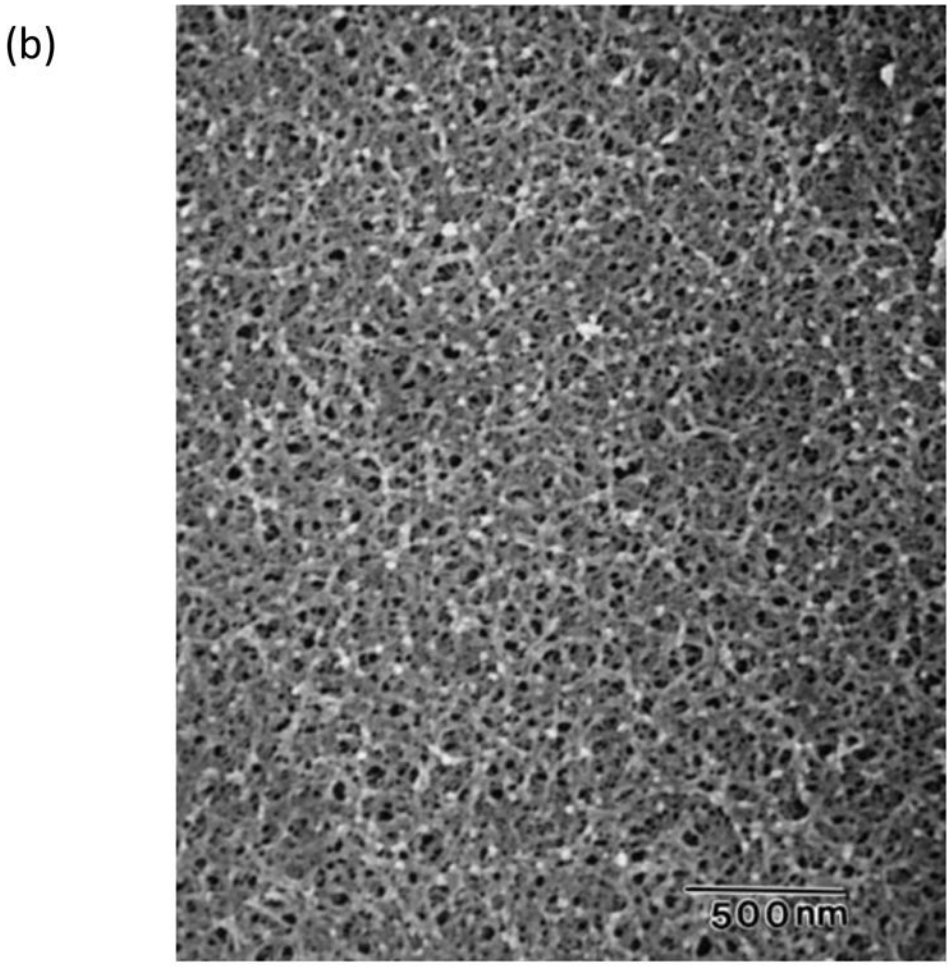
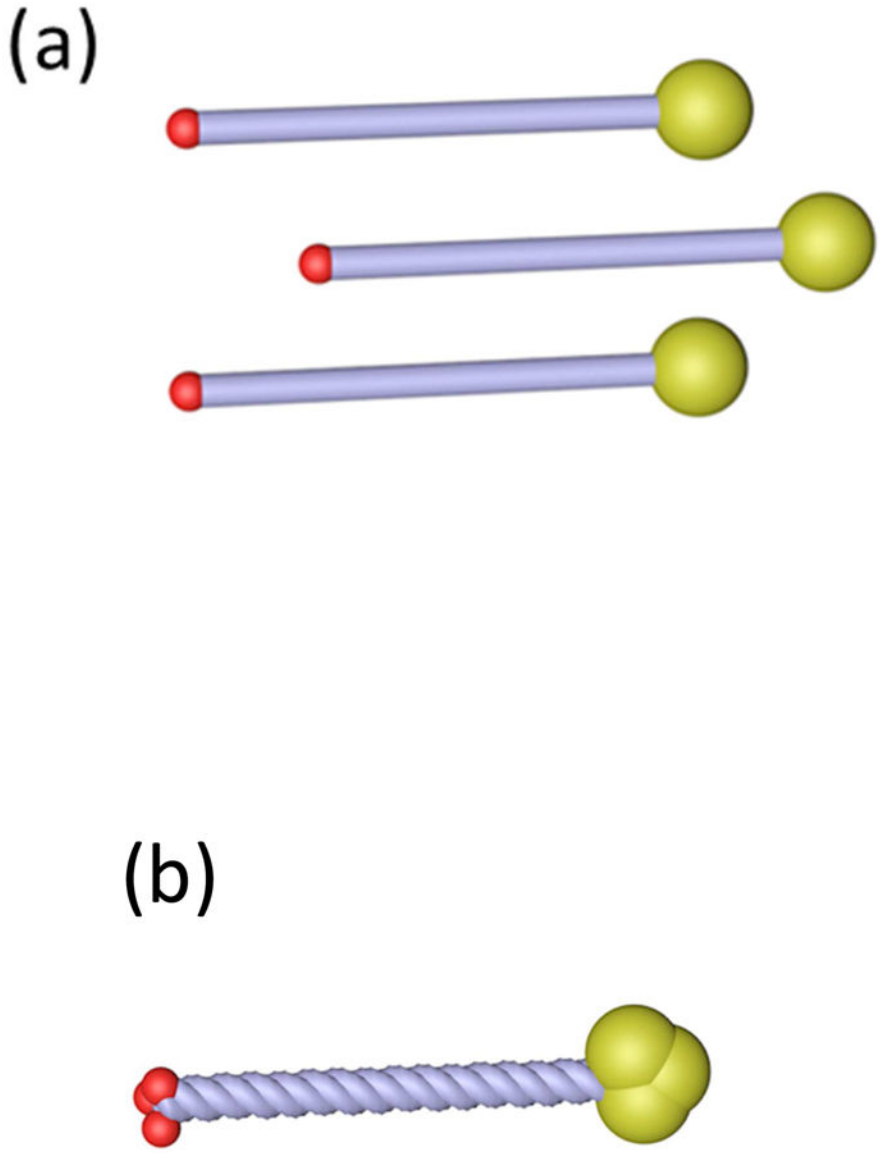
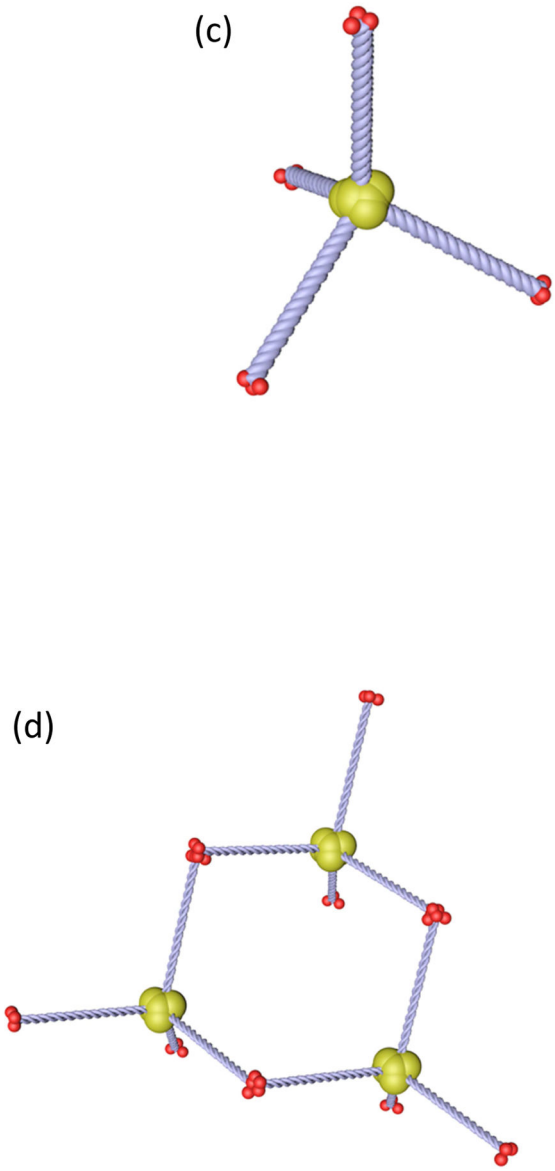


Figure 1. The basements membranes of the canine cornea

(a) Scanning electron micrograph of the canine corneal epithelial basement membrane. The basement membrane has an intricate surface topography consisting of a meshwork of fibers and pores. (Reprinted with permission from Bentley et al., 2001. ©Association for Research in Vision and Ophthalmology) (b) Scanning electron micrograph of Descemet's membrane of the canine cornea. The complex topography of intertwined fibers and pores of varying sizes is similar to the topography found in the epithelial basement membrane. (Reprinted with permission from Abrams et al., 2002.)





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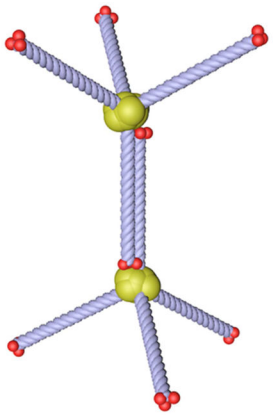

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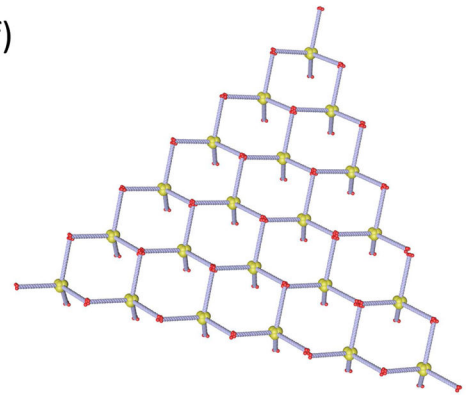

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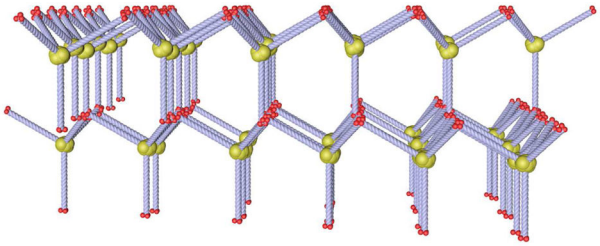

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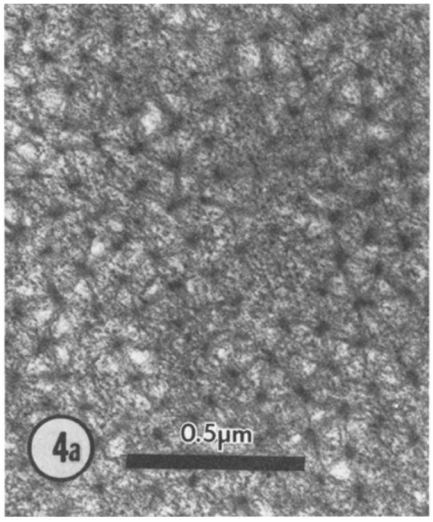

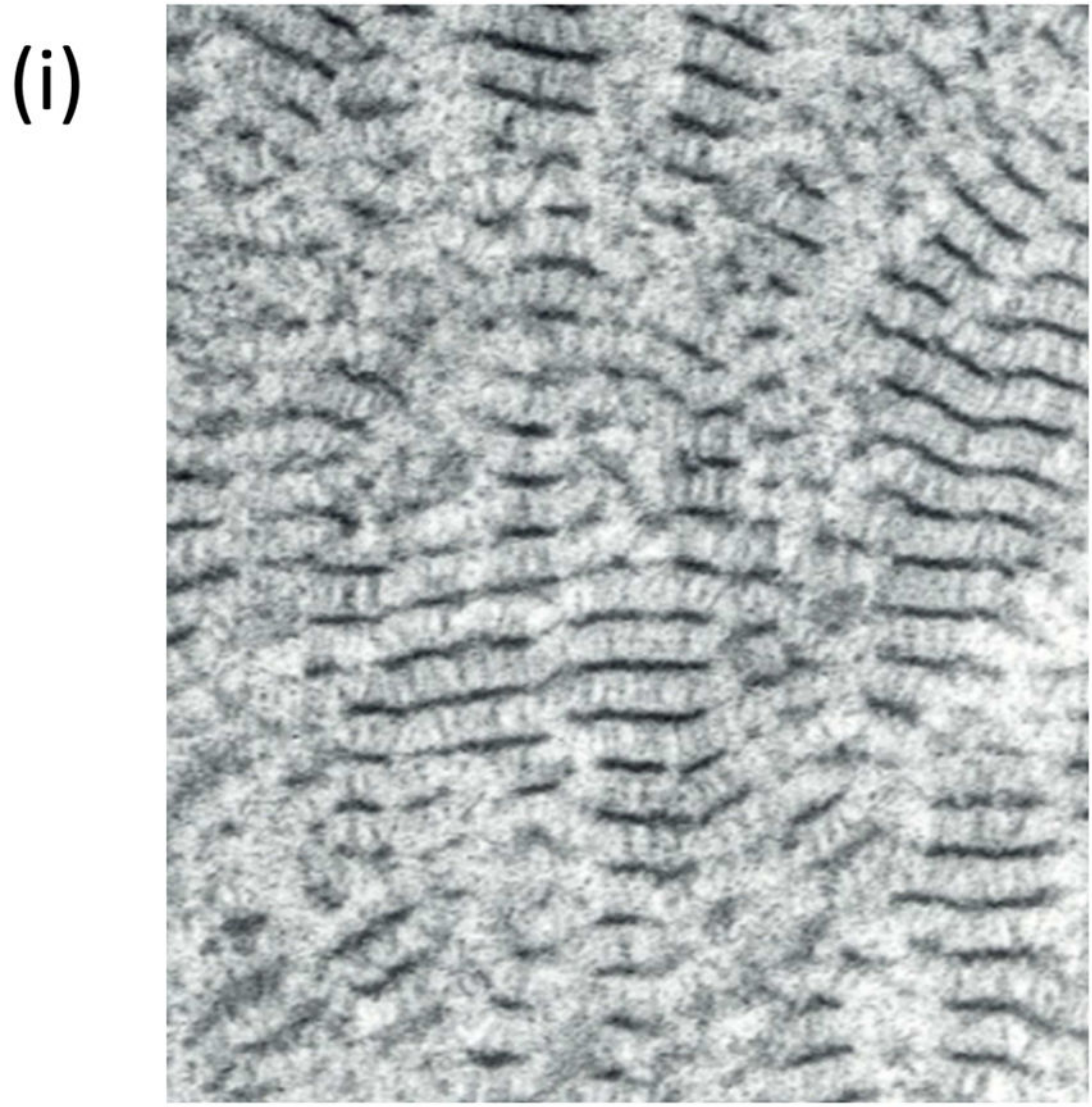

Figure 2. The assembly of Collagen VIII, an extracellular matrix protein critical in the assembly of Descemet's membrane

It comprises two types of polypeptide chains, α1(VIII) and α2(VIII) consisting of (a) two globular domains, the larger on the C-terminal side, connected by a rod-like triple-helical domain. (b) These polypeptides can form homotrimers. (c) Four of these homotrimers may associate through their C-terminal domains to form tetrahedral assemblies. These tetrahedra may assemble further via (d) N- to N-terminal interactions or (e) N- to C-terminal interactions. (f) Extended networks of Collagen VIII assemblies may form a hexagonal network that (g) stacks vertically, shown here based on N- to N-terminal interactions. This theorized assembly pattern of Collagen VIII corresponds to the ultrastructure of Collagen VIII, imaged through transmission electron microscopy in Descemet's membrane. (h) In the en face section, Collagen VIII appears as a hexagonal network, whereas (i) in the transverse section it appears as parallel bands. The imaged ultrastructure supports the theorized assembly of Collagen VIII. ((h) reprinted with permission from Sawada 1982. (i) reprinted

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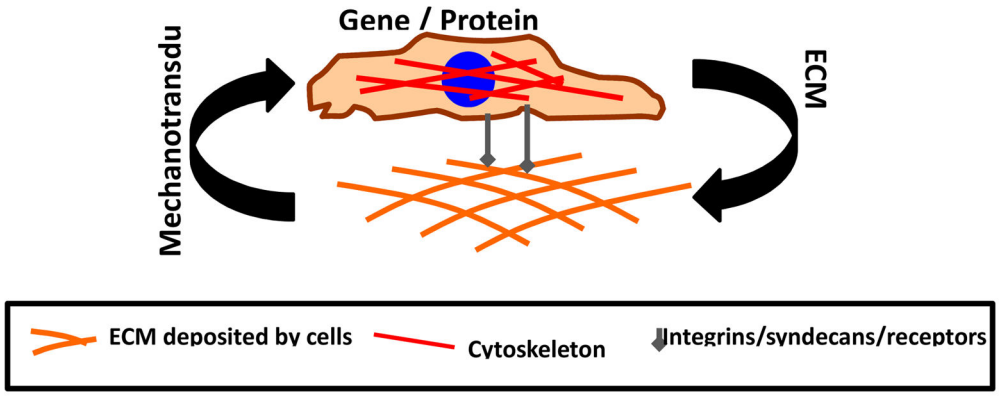

Figure 3. Dynamic Reciprocity

Cells synthesize ECM proteins and deposit them into the extracellular space. The proteins assemble the matrix, presenting a rich set of topography and modulus cues to the cells. Integrins, syndecans, and other receptors mechanotransduce biophysical cues into the cells. Signaling molecules and the cytoskeleton convey these signals to the nucleus, where they influence cell behavior in many ways, including through changes in the expression of ECM genes and proteins.

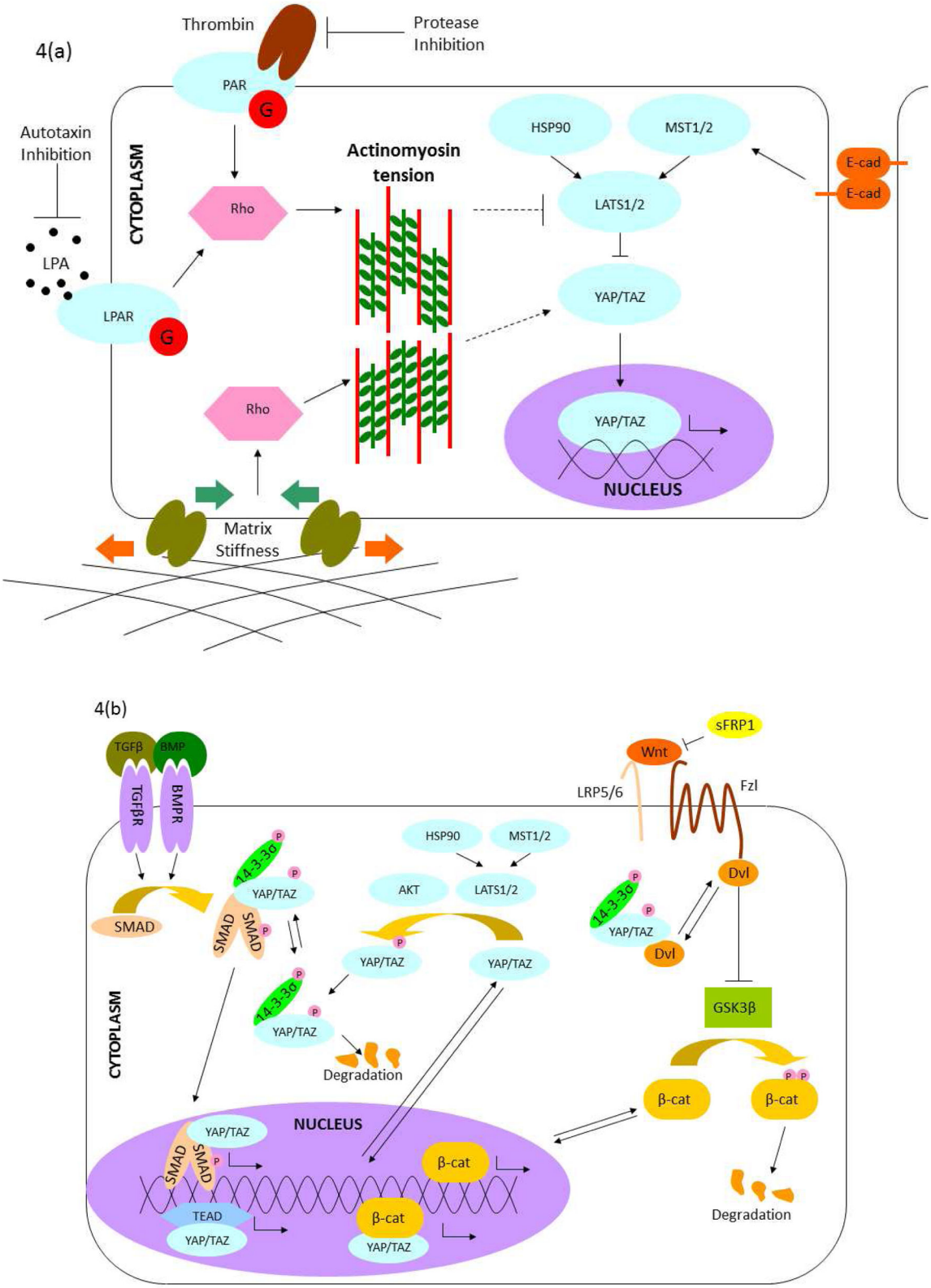

Figure 4. Signaling pathways linked to mechanotransduction

(a) Mechanical regulation of the Hippo pathway. Hippo is regulated by multiple signals generated by the physical (matrix stiffness) and biochemical (e.g. LPA, thrombin) environment. Importantly, many of these signals are modulated by tension in the actinomyosin cytoskeleton. Modulation of cytoskeletal mechanics through G-protein coupled receptors and matrix biophysics can likewise inhibit YAP/TAZ directly at the nuclear translocation stage or through activation of Hippo components. Note: This schematic is simplified to clarify the major components in the mechanical regulation of YAP/TAZ signaling. (b) Crosstalk between YAP/TAZ and TGF-β, and between YAP/TAZ and Wnt. TGF-β superfamily signaling is initiated by the binding of an extracellular ligand (e.g. TGF-β and BMP), which leads to the phosphorylation of SMADs and the formation of a complex with a Co-SMAD and 14-3-3s. After translocation to the nucleus, these complexes initiate the TGF-β/BMP transcriptional program. The SMAD complex also interacts with YAP/TAZ to initiate different transcriptional programs in the nucleus. Canonical Wnt is initiated by the binding of a Wnt ligand to the Fzd/LRP receptor complex. This induces the inhibitory behavior of Dvl on the Axin/APC/GSK3b complex, freeing β-catenin to translocate to the nucleus and initiate the Wnt transcriptional program. YAP/TAZ can inhibit Wnt signaling through inhibition of Dvl in the cytoplasm (TAZ) or in the nucleus (YAP) or cytoplasmic sequestration of β-catenin (YAP). Alternatively, YAP can encourage the transcriptional activity of β-catenin. Note: This schematic is simplified to clarify the intersections of YAP/TAZ and Wnt signaling. (Adapted with permission from Morgan, 2013)

Table 1

A comparison of measurements of the stiffness of Descemet's membrane in various species using different several analytical methods. In the mechanical interferometry imaging data set, the "short term" value refers to an instantaneous measurement whereas the "long term" values refers to a time dependent measurement including non-linear effects in response to constant stress over a 200 sec interval. Atomic Force Microscopy measurements were instantaneous. Measured values are highly dependent on analytical methods, making it necessary to consider the strengths and limitations of each method during experimental design and data interpretation.

Species	Modulus	Measurement technique
Rat	2·81 ± 0·51 MPa[50]	Tensile testing
Cow	6·14 ± 0·41 MPa[50]	Tensile testing
Pig	4·29 ± 0·35 MPa[50]	Tensile testing
Human	2·57 ± 0·37 MPa[50] 50 ± 17.8 kPa[45] 339.2 ± 22.2 kPa (short term) and 20.2 ± 0.71 kPa (long term)[43] 1.8 ± 0.8 MPa (hydrated) and 4.8 ± 1.2 GPa (dehydrated)[163]	Tensile testing Atomic Force Microscopy Mechanical Interferometry Imaging
Rabbit	11.7 ± 7.4 kPa[47]	Atomic Force Microscopy

Table 2

Elastic moduli of corneal layers as measured by atomic force microscopy (AFM) in humans and rabbits.

Corneal layer	**Elastic Modulus**	
	Humans	**Rabbits**
Anterior Basement Membrane	7.5 ± 4.2 kPa[45]	4.5 ± 1.2 kPa[47]
Bowman's Layer	109.8 ± 13.2 kPa[46]	Absent
Stroma	33.1 ± 6.1 kPa [46]	1.1 ± 0.6 kPa (anterior face) 0.38 ± 0.22 kPa (posterior face)[47]
Descemet's membrane	50 ± 17.8 kPa[45] 1.8 ± 0.8 MPa (hydrated) and 4.8 ± 1.2 GPa (dehydrated)[163]	11.7 ± 7.4 kPa[47]
Endothelium		4.1 ± 1.7 kPa[47]