BIOPHYSICS

To buckle or not to buckle

Epithelial layers under compression avoid buckling by active contraction, but only up to a well-defined threshold at 35% strain, beyond which buckling occurs.

Ulrich S. Schwarz

Buckling of thin beams and sheets under compression is a ubiquitous phenomenon that can be detrimental or beneficial, depending on context. Often it is related to the failure of a load-carrying structure, like a bridge, and therefore should be avoided. Sometimes, however, it is put to good use: for example, when absorbing impact energy with a porous structure. The same considerations also apply to biological structures carrying mechanical load. In a new study now published in *Nature Materials*, a team led by Guillaume Charras shows that epithelial cell layers have a well-defined transition point at 35% compressive strain up to which they avoid buckling by active contraction[1]. Only when compression exceeds this critical point, buckling occurs. By regulating this transition point, epithelial cell layers can tune their mechanical performance as needed.

Epithelial cell layers result from a general strategy often pursued by biological systems when generating spatial structure in the three-dimensional space we live in: cells first form thin, effectively two-dimensional layers, which then can bend and twist in three-dimensional space.

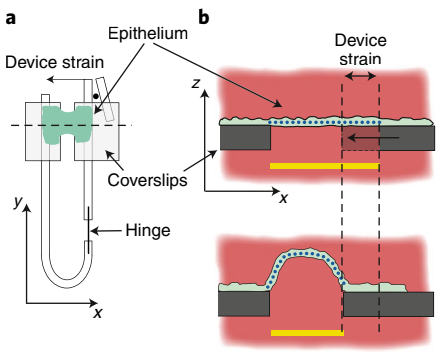

Fig. 1 | A technique for applying either tensile or compressive strain onto epithelial monolayers. **a**, The epithelial monolayer is placed between two coverslips, with one stationary and the other capable of displacement via the flexible right arm. **b**, As the right arm is displaced inward, the suspended epithelial monolayer buckles under compression. Reproduced from ref. [1], Springer Nature Ltd.

This strategy can lead to the intricately folded structures that we observe in our internal organs, such as lung, kidney or intestines. Most of the interfaces between different compartments in our body are lined by such epithelial sheets. In many cases, these are simple monolayers, but they provide very robust and sophisticated barriers, as we realize when they are disrupted, such as during wounding. Apart from their ability to transport ions and molecules from one compartment to another, epithelial layers have an important role in maintaining mechanical integrity of these interfaces over many strain cycles and under high mechanical load. Thus, epithelial layers are of large interest to materials science, because they can teach us which solutions nature has evolved to ensure superior function in a mechanically challenging environment.

One challenge in investigating the properties of epithelial layers is that in vivo they are always anchored to a basal lamina of extracellular matrix. This makes it difficult to distinguish if the observed mechanical properties are determined by the cells or by the extracellular matrix. Previously, Charras and colleagues developed a creative way to cope with this challenge: they first cultured epithelial cells on a layer of collagen that was then removed by enzymatic digestion[2]. By stretching the freely suspended monolayer between two rods (Fig. 1a), they found that these layers can tolerate more than 100% of extension before rupture occurred of the cell–cell junctions. The authors also demonstrated in a follow-on study that after a 30% stretch, relaxation occurs within a minute in a biphasic manner, first through power-law rheology and subsequently in an exponential manner[3].

However, thin layers are very asymmetric in their response to extension versus compression. Charras and colleagues have now used their apparatus also for compression tests (Fig. 1b) and found that for fast (millisecond) compression, epithelial sheets buckled up as expected. Surprisingly, however, the sheets subsequently flattened on a timescale of tens of seconds, due to the contractile nature of the actomyosin network (Fig. 2a). For slow (seconds)

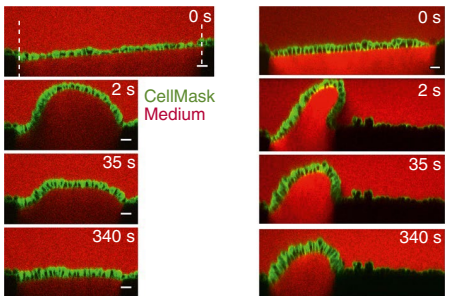

Fig. 2 | Changes in the planarity of epithelial monolayers undergoing compressive strain. When modest compressive strain was quickly applied to the monolayer, it took on an arched shape that was short-lived and flattened within a minute. However, when the compressive strain was over 35%, the buckle was stable for over 10 min and did not flatten. Reproduced from ref. [1], Springer Nature Ltd.

compression, the actomyosin was able to maintain the flat state at all times. Of course, there have to be limits to this contraction, and indeed the researchers identified a threshold of 35% compressive strain at which buckling eventually occurred. Beyond this threshold, the monolayer did not flatten, even if compression was applied very slowly (Fig. 2b). Using a zero-dimensional elastic model for the cell monolayer, they showed that the critical buckling threshold around $\varepsilon_b = 0.35$ emerged as the ratio of active monolayer tension $\sigma_a = 240$ Pa to monolayer stiffness $E = 640$ Pa, both of which can be measured independently and far away from the threshold. Different pharmacological perturbations changed the values for both σ_a and E, but the buckling threshold was always close to $\varepsilon_b = \sigma_a/E$. These findings provide a clear physical explanation for the observed behaviour: the monolayer is initially under active prestress and buckling occurs once this prestress is completely compensated by compression. However, the cellular response needs time; transient buckling can thus occur below the threshold for fast compression. By regulating its active tension, the monolayer can tune the exact value of the buckling threshold to its needs.

Going beyond monolayers from kidney cells, the authors also demonstrated the same mechanisms in multilayered epithelia from skin cells. Regarding the biological function of this universal behaviour, one can speculate that epithelia tend to buffer the effects of modest compression in order to limit the impairment to normal physiological function (such as gas exchange in the lungs), but they buckle at large compression as a safety mechanism to avoid damage to the cells. The view of using actomyosin tension as a means to ensure physiological function nicely ties in with the concept of 'tensional homeostasis'[4], which states that cells adjust their contractility to meet the mechanical challenges imposed by their environment[5]. Experiments on single cells have shown that the actomyosin cannot always completely compensate for external stretch, but can at least buffer it[6]. The complete theoretical model suggests that incomplete recovery and memory during fast compression, which was demonstrated experimentally, results from a viscous component, which in turn might be related to the force–velocity relation of the myosin motors[7]. Surprisingly, the authors did not find many changes in the cell–cell junctions, which often are associated with epithelial homeostasis in vivo[8]. Further work will be required to fully understand how epithelial and other tissues behave under the large range of physiologically relevant mechanical loading conditions. However, the findings reported in this latest study have quantitatively clarified the physical mechanisms behind the adaptation of epithelial layers to compression. ❐

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ELECTROCALORICS

Electrocalorics hit the top

A first-order ferroelectric phase transition is driven supercritically in multilayer capacitors of $PbSc_{0.5}Ta_{0.5}O_3$, enabling an electrocaloric response of 5.5 K near room temperature.

M. Otončar and B. Dkhil

Cooling of food, cars and houses or working environments represents about 20% of world energy consumption, and this percentage is increasing because of increasing living standards of the world's population[1]. The prevailing cooling technology is based on vapour-compression, which relies on a closed-loop cycle by compressing, condensing, expanding and evaporating a refrigerant gas. While mature and widely used, this technology is approaching the limits of energy efficiency improvements and poses a risk to the environment because it uses harmful hydrofluorocarbon-based refrigerants, which have a high global warming potential (GWP)[2]. Lower-GWP substitute gases are feasible; however, reduced GWP comes with drawbacks related to toxicity, flammability and lower efficiency. These constraints present an opportunity for non-vapour-compression technologies that use solid refrigerants as a working body, thus eliminating direct greenhouse gas emissions. Among these alternatives are the so-called caloric materials[3] (that is, elastocalorics, magnetocalorics and electrocalorics (ECs)), which undergo a significant adiabatic temperature change ΔT and/or isothermal entropy change ΔS near their phase

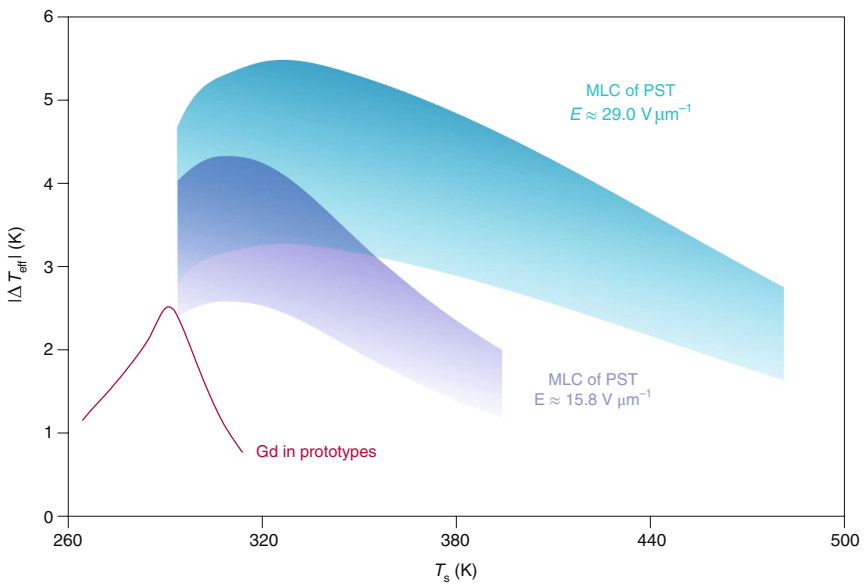

Fig. 1 | Large EC effects over a wide range of operating temperatures in Sc/Ta-ordered PST MLC. Effective EC temperature change $|\Delta T_{eff}|$ from direct measurements as a function of starting temperature T_s, for fields of $E = 15.8$ V μm^{-1} (violet) and 29 V μm^{-1} (blue). Upper ΔT_i limit of the shaded regions assumes no internal thermalization between active and non-active volumes of the MLC prior to useful heat transfer, while the lower one (of $0.60|\Delta T_i|$) assumes thermalization. For comparison, the red line shows $|\Delta T_{eff}|$ versus T_s for a bed of commercial-grade Gd spheres driven with permanent magnets and applied magnetic field of ~1.4 T, giving values lower by a factor of two over a narrower operating temperature range.