Quick-release medical tape

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Medical tape that provides secure fixation of life-sustaining and -monitoring devices with quick, easy, damage-free removal represents a longstanding unmet medical need in neonatal care. During removal of current medical tapes, crack propagation occurs at the adhesive–skin interface, which is also the interface responsible for device fixation. By designing quick-release medical tape to undergo crack propagation between the backing and adhesive layers, we decouple removal and device fixation, enabling dual functionality. We created an ordered adhesive/antiadhesive composite intermediary layer between the medical tape backing and adhesive for which we achieve tunable peel removal force, while maintaining high shear adhesion to secure medical devices. We elucidate the relationship between the spatial ordering of adhesive and antiadhesive regions to create a fully tunable system that achieves strong device fixation and quick, easy, damage-free device removal. We also described ways of neutralizing the residual adhesive on the skin and have observed that thick continuous films of adhesive are easier to remove than the thin islands associated with residual adhesive left by current medical tapes.

neonatal injury | sensitive skin

Medical adhesive removal causes more than 1.5 million injuries each year in the United States alone (1–3). Injuries in neonates range in severity from skin irritation to permanent facial scarring or lifelong restriction of motion in the case of fibrosis surrounding joints (1). In the neonatal intensive care unit, medical adhesives are ubiquitous, affixing life-sustaining and life-monitoring devices to not yet or newly keratinized, sensitive skin (1). Whereas neonatal skin lacks an epidermis, skin in the elderly population can become thin and loosely anchored, making both populations prone to skin damage during adhesive removal (4). Because more than 1 in 10 of births in the United States are preterm, and the elderly population is growing, there is a clear need for designing a medical tape for patients with sensitive skin (1–5). Commonly, neonatal endotracheal (ET) tubes are affixed to the faces and heads of newborns, enabling assisted respiration. Motion of only millimeters can cause misplacement of the ET tube, which requires emergency removal and replacement. In many cases, emergency ET-tube adjustment leads to adhesive removal injury. Clearly, there is a strong unmet clinical need for tape that both securely affixes devices to sensitive skin and produces minimal dermal stress during rapid removal.

Previous work to design adhesives for sensitive skin focused on altering the adhesive–skin interface, modifying the flexibility of backing layer, or gecko-inspired adhesives (1–8). Although these approaches may improve safety, they exhibit reduced efficacy with respect to device fixation (1). Additionally, stretch tape–based approaches are unsuitable for use in neonatal applications because they apply excessive tissue compression attributable to the elastic recoil of the backing materials, which can impair circulation. Recognizing that the backing layer of tapes serves an essential physical/mechanical role after application to the skin, yet unnecessarily contributes to increased removal forces during tape removal, we developed an approach to rapidly decouple the backing from the adhesive layer without altering well-functioning medical adhesives. We aimed to achieve this through creating a dual functional adhesive interface between the adhesive and backing layers, leaving the clinically effective adhesive–skin interface unchanged. Our goal was to increase safety during removal

while maximizing device-fixation efficacy of commercially available tapes by creating an anisotropic adhesive interface between the backing and adhesive layers. We created a backing–adhesive interface that possesses high shear strength, with low peel force, so that the tape can provide device fixation and quick, injury-free removal.

Our quick-release tape design achieves low peel force at the backing–adhesive interface, while preserving high shear strength at both the skin–adhesive and backing–adhesive interfaces. Additionally, quick-release tape demonstrates high normal peel adhesion of an affixed device at the adhesive–skin interface, such that the intact quick-release medical tape will resist strain caused by motion in all directions. High shear strength and normal adhesion are essential to maintain device fixation during motion of the skin relative to the adhesive layer of the quick-release medical tape. Achieving low peel strength at the backing–adhesive interface is essential for quick, safe removal. Our design leaves the skin-contacting adhesive layer unchanged, relying on commercially available pressure sensitive acrylate adhesives with well-characterized performance in clinical settings. Commercially available acrylate adhesives for medical tapes have passed Draize testing for skin irritation during long-term use, despite islands of adhesive remaining on the skin following removal. This indicates that residual adhesive is nonirritating. Furthermore, residual adhesive left by medical tapes is sloughed off naturally overtime with skin turnover, providing a natural, damage-free removal mechanism. Because the backing layer provides tapes with the majority of their cohesive mechanical strength, we thought decoupling the backing from the adhesive layer before tape removal would enable quick, damage-free device removal from the skin. Mimicking the easily peeled and highly shear-resistant multilaminate structure of the phyllosilicate mineral, mica (9), we used a three-layer design approach: (*i*) backing; (*ii*) release liner (RL); and (*iii*) adhesive. Peeling the quick-release tape backing from the adhesive layer causes stress localization close to crack front, such that only a small area of adhesive resists crack initiation and propagation. As a result, similar to peeling layers of mica, peeling the quick-release backing from the adhesive layer requires little force. By contrast, as with sheering layers of mica, pulling a medical device affixed by quick-release tape causes delocalized sheer stress over a large area of adhesive. The large area of adhesive in contact with the backing provides significant resistance to crack initiation, resulting in secure device fixation.

To bypass the cohesive mechanical strength of tapes that is typically dominated by the properties of the backing layer, we coated the adhesive-contacting surface of a backing layer with RL, followed by laser etching to expose the underlying polymer. This enabled microscale patterned adhesive and nonadhesive domains. Our approach permitted precise tuning of the bulk adhesive properties at the microscale using a physical process.

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Additionally, the spatial resolution afforded by physical patterning enabled quantification of the relationship between composition and backing adhesion. Chemical means of adjusting the adhesiveness of RLs, often referred to as release modifying agents, were avoided because of potential leaching concerns, especially poignant in neonatal care. By altering only the backing–adhesive interface, the skin–adhesive interface remains unchanged from standard medical tapes, for which the skin-irritability profiles of adhesives are well-characterized. Also, by coating the backing with RL and selectively etching away microscale regions to create an anisotropic backing–adhesive interface, the backing materials can remain unchanged, representing minimal processing alterations in the construction of quick-release medical tapes to ensure safety and scalability.

Results

Fig. 1*A* is a representative photograph of a preterm infant, who during adhesive removal from the left dorsal metatarsal skin sustained mild to moderate skin irritation, as is a common occurrence in neonatal intensive care. The ubiquitous use of medical adhesives in neonatal care and the frequent damage caused during removal highlight a clear need to design medical adhesives that strongly secure devices to the skin but can be easily removed.

A standard, two-layer (backing and adhesive) medical tape is shown in Fig. 1*Bi* while affixed to sensitive skin and the damage its removal can cause. Our quick-release, three-layer (backing, intermediary layer, and adhesive) medical tape solution is shown in Fig. 1*Bii*. The RL coating (0.5–0.8 μm intermediary layer) and backing layer (50 μm thick) are peeled away to leave residual adhesive (50 μm thick) on the intact skin. Quick-release medical tape leaves a greater quantity of adhesive behind by design, such that the residual adhesive is continuous and sufficiently thick to facilitate removal from the skin using a rolling motion that minimizes dermal strain (Fig. 1*Bii*). Additionally, we describe a neutralization strategy and have observed that the continuous film of residual adhesive can be relatively easily removed by rolling, unlike the thin islands of adhesive frequently left after the removal of standard medical tapes. By designing the tape to undergo adhesive failure at the intermediary layer-adhesive interface, the stress and strain experienced by the skin even during rapid removal is minimized.

To experimentally illustrate the concept of damage free removal, quick-release medical tape and conventional medical tapes were affixed to origami paper (Fig. 1*Ci*). Rapid removal, simulating an emergency response scenario shows that conventional tapes rip the colored portion of the origami paper exposing the underlying white paper, whereas quick-release tape leaves residual adhesive on the paper and causes no tearing (Fig. 1*Cii*). Origami paper was used as a proxy for sensitive neonatal skin given that it is easily damaged during rapid (5 cm/s) medical tape removal. Origami paper mimics sensitive-skin behavior under the tested conditions in that removal of adhesive tape causes tearing of the superficial layer from the deep layer, as observed in tape stripping of skin (10). Given that the quick-release tape removed under the same conditions did not induce any tearing infers that it transmits significantly less force to the underlying substrate than conventional tapes.

Results from the Pressure Sensitive Tape Council (PSTC) 90° peel test show that the solvent cast acrylate based adhesive used in our studies (without the intermediary patterned antiadhesive layer) is strong (Fig. 2*A*). With a standard polyethylene terephthalate (PET) test backing, the average and maximum peel forces are more than twice that of commercial plastic- and paper-backed medical tapes and more than an order of magnitude greater than tape designed for neonates meant for gentle removal (NeoFlex; NeoTech). Tape peel was self-tested on the skin of the medial ventral forearm and produced similar trends to peel from stainless steel (Fig. 2*B*). Although the trend is similar, the average and maximum peel forces are lower in each case in comparison with the stainless steel, which is in agreement with trends observed with other pressure sensitive adhesives (11). Although increased adhesive strength is not required for all neonatal medical tape functions, we elected to use a strong adhesive to emphasize that we could achieve rapid, damage-free removal without sacrificing adhesive strength.

To determine the macroscale effect of varying the surface area of interaction between the backing layer and the adhesive layer, through altering the percent coverage of the PET backing with antiadhesive RL coating, peel tests were performed on backings in which the exposed PET backing area was 100%, 75%, 50%, 25%, and 0%, with the remainder in each case being a strip of RL-coated PET aligned lengthwise with the middle of the tape (Fig. 2*Ci*). PET (100% PET) showed strong adhesion to the acrylic-based adhesive, whereas RL-coated PET (0% PET) exhibited negligible adhesion to the same adhesive. Both average and maximum 90° peel forces exhibited an inverse cubic function curve fit as a function of exposed PET (Fig. 2*Cii*). The inverse cubic function dependence of peel force on surface area of interaction infers that Van der Waals forces, as predicted by the Derjaguin approximation ($F \sim 1/D^3$), dominate the RL-coated backing/adhesive interaction, rather than chemical bonding or polymer chain interpenetration (9, 12). Additionally, the macroscale investigation demonstrated that adhesive regions of the backing layer should be submillimeter in scale to avoid

Fig. 1. Quick-release medical tape avoids damage to underlying skin during removal. (*A*) Photograph of a preterm neonate (courtesy of Barb Haney, Children's Mercy Hospital, Kansas City, MO) showing a mild to moderate skin injury sustained during adhesive removal. (*Bi*) Schematic showing how conventional two-layer medical tape removal can damage sensitive skin on removal. Conventional medical tape removal typically leaves a small amount of residual adhesive on the skin. (*Bii*) Removal of the coated backing layer (backing and intermediary layer) from the adhesive leaves residual adhesive on skin for a damage-free removal of quick-release medical tape. Residual adhesive can then be removed from the skin with minimal strain by using a rolling motion. (*Ci*) Commercial paper tape, plastic tape, and quick-release tape affixed to paper substrate. (*Cii*) Commercial tapes rip the underlying surface upon removal, as observed in tape stripping of human skin, whereas quick-release tape leaves behind adhesive, and paper substrate remains fully intact.
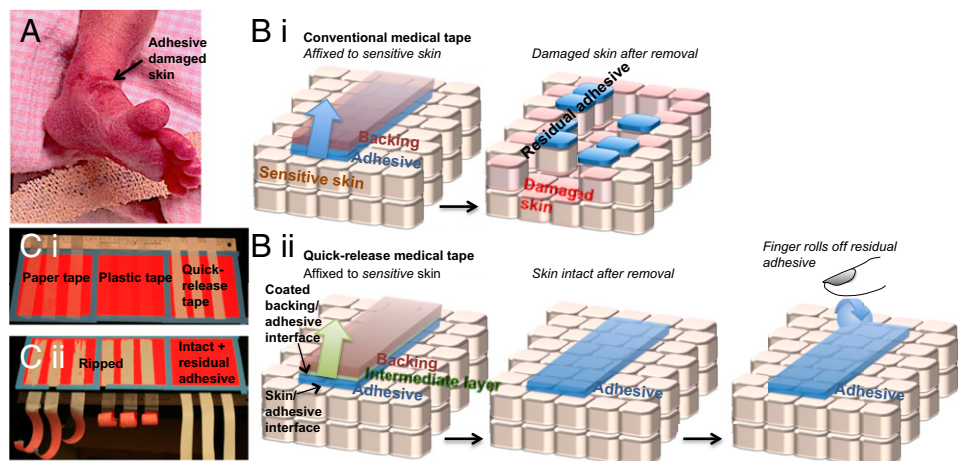
Fig. 2. Peel adhesion correlates with the percentage interfacial area covered by RL. (*Ai*, *Bi*, and *Ci*) Ninety-degree peel test setups under conditions recommended by the PSTC (*Ai*), photograph of peel self-tested on medial ventral forearm skin (*Bi*), and macroscale strips of RL and backing PET (*Ci*). (*Aii*) In the PSTC 90° peel from polished stainless steel, the PET-backed acrylic adhesive tape exhibits greater average and maximum peel force than commercial plastic, paper, and NeoFlex tapes. (*Bii*) Peel force self-tested on forearm skin follows the trends of peel tests performed under PSTC testing conditions on a polished stainless steel plate but at slightly lower forces. (*Cii*) PET without RL coating has high peel force from acrylic acid–derived adhesive, and RL-coated PET (with no exposed PET; denoted as 0 on the *x* axes) presents very low peel force. Macroscale strips of RL-coated PET within full thickness PET backings exhibit peel-adhesion forces in proportion to the area percentage of exposed PET. The relationships between average and maximum peel forces and percentage area coverage of PET are described by inverse cubic functions of fractional PET coverage ($R^2 > 0.99$). The inverse cubic dependence of peel force on interfacial contact area infers primarily Van der Waals bonding

between the backing and adhesive layers in the presence of RL coatings. Red lines show the peel forces of plastic medical tape self-tested on forearm skin. (*D*) Movie S1 shows crack propagation between the 1-mm etched grid line backing and acrylate adhesive layers at a speed of 0.5 mm/s. The crack propagates quickly over RL-coated sections and pauses within etched lines that are perpendicular to the peel direction and parallel to the crack front. Quantification of crack average velocity is plotted as a function of time for three representative periods in which the crack propagates from one etched line to another. Slowing in crack velocity indicates the adhesive is more adherent to the underlying PET compared with the RL-coated surfaces. All plots show $n = 3$ (mean ± SD). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

heterogeneous crack propagation during backing removal. Like quick-release medical tape, mica sheets that also adhere primarily by Van der Waals forces exhibit low peel force and high shear strength (9). When further probing the mechanism of adhesion between laser-etched backings and acrylate adhesives, high-speed (100-Hz) video analysis of crack propagation shows that the crack propagates faster where RL contacts the adhesive, whereas the crack propagates slowly at the laser etched lines where the adhesive firmly attaches to the PET backing. Fig. 2*D* plots average crack propagation velocity as a function of time, which clearly shows crack propagation slows within PET features of laser etched lines parallel to the crack propagation front (Movie S1).

Peel-testing results indicate that peel adhesion between the backing and adhesive layers can be adjusted as high as a standard medical tape with 100% backing exposed, to as low as a very weak adhesive when the backing is completely covered with the 0.5- to 0.8-μm-thick RL coating. Importantly, the addition of RL coatings did not substantially reduce the shear-adhesion properties between the backing and adhesive layers, creating the desired dual-functional adhesive interface. This indicates that crack initiation between the backing and adhesive layers has a high energy barrier, whereas crack propagation requires minimal energy in the presence of a substantial RL coating coverage. The ability of micropatterned RLs to maintain strong shear adhesion while reducing peel strength has not been described previously and is responsible for the observed dual-adhesive functionality. By varying the percent backing exposed, the peel force of the backing from the adhesive can be adjusted to any value within the bounds of the adhesive strength of the upper bound of the pure polymer backing and the lower bound of the fully coated RL backing. During peel testing on stainless steel, the adhesive in contact

with the PET remains adhered to the backing, whereas the adhesive contacting the RL remains on the steel substrate. In the case of micropatterned quick-release medical tape at the backing, RL, and adhesive junctures in the backing/adhesive plane, the propagating crack can continue to propagate either along the backing/adhesive plane, leaving residual adhesive on the skin, or along the adhesive/skin plane, leaving residual adhesive on the backing. When the crack propagation continues at the backing–adhesive interface, residual adhesive remains on the skin. In the event of crack bifurcation, residual adhesive will remain on the adhesive regions of the backing (e.g., exposed PET). The geometry of the adhesive features, the interfacial chemistry and rheology of the adhesive govern crack propagation during peel testing (13). We observe that submillimeter adhesive features provide sufficiently small interfacial contact area such that crack propagation occurs homogenously in an adhesive fashion between the patterned backing and adhesive layers. Larger features create sufficient interfacial contact between the adhesive portions of the backing and the adhesive such that the adhesive will cohesively fail, which impairs quick release with minimal force.

Because of the small features created by laser-etched lines, crack propagation occurs homogeneously along the adhesive-backing interface during peel testing. Therefore, laser-etched lines in RL-coated PET can increase the peel adhesion force uniformly across the surface of the backing layer to create a quick-release backing. Unlike the separation of adhesive attributable to leading-edge crack bifurcation and cohesive failure observed in the case of macrosized strips of RL and PET (as seen in Fig. 2 *Ci* and *Cii*), the adhesive remains entirely on the substrate after peeling of the micropatterned quick-release backings (as seen in Fig. 3).
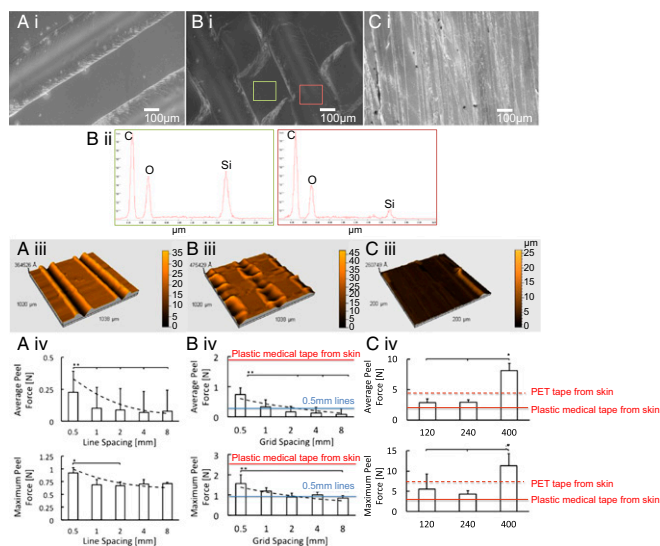
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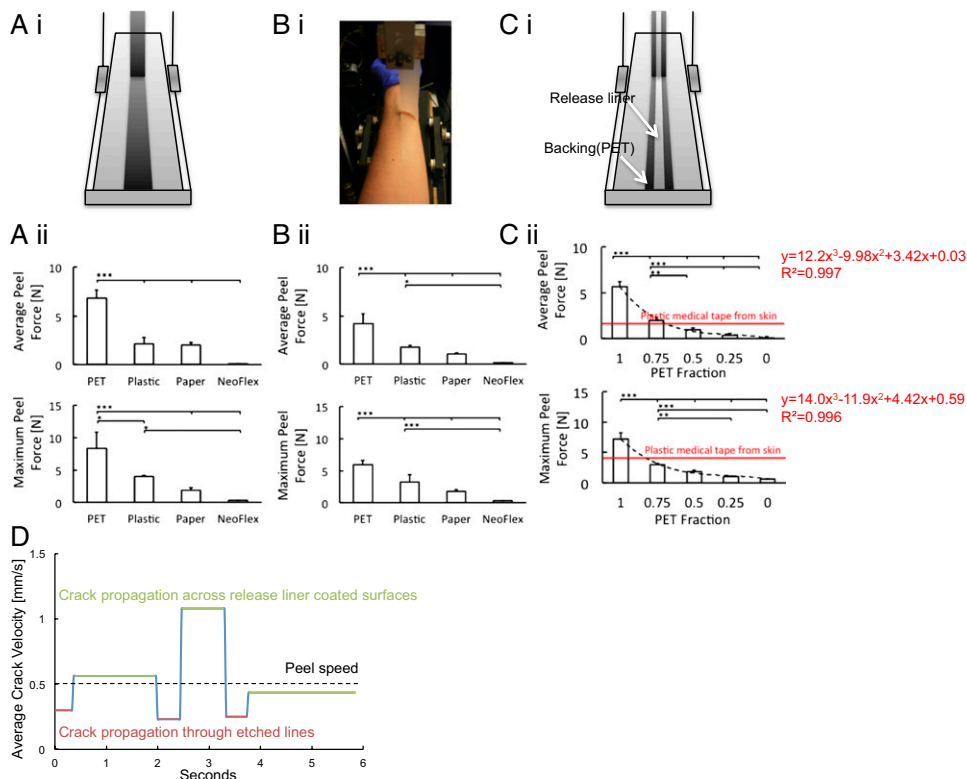
Fig. 3. Patterning creates microscale adhesive and antiadhesive regions. (*Ai*, *Bi*, *Ci*) Field emission scanning electron micrographs of laser-etched lines (*Ai*), laser-etched grid lines (*Bi*), and 400-grit sandpaper-roughened patterned quick-release medical tape backings (*Ci*). (*Bii*) Elemental analyses performed by energy-dispersive spectroscopy analysis in a RL-coated region (green rectangle) and a laser-etched region (red rectangle). The RL-coated regions in all samples showed higher silicon content relative to carbon and oxygen content than in the etched or abraded regions. (*Aiii*, *Biii*, and *Ciii*) Three-dimensional optical profiles of laser-etched lines, laser-etched grid lines, and 400-grit sandpaper-roughened backings (left to right). (*Aiv*) Laser-etched lines increase average backing peel adhesion force when spaced 0.5 mm apart compared with widely spaced etched lines ($P < 0.01$). A similar trend is observed for the maximum peel force. (*Biv*) Laser-etched square grid lines increase backing peel adhesion in proportion with the increased area percentage of exposed PET. Both laser-etched lines and grid lines exhibit average and maximum peel force trends in accordance with the inverse cubic curve fits to peel forces of macroscale strips of RL and PET as a function of PET fraction. (*Civ*) Sandpaper-roughened quick-release medical tape shows significantly increased backing peel force (*y* axis) related to the grit (*x* axis, which corresponds to the sand particle size of sandpaper, higher grit corresponds with smaller particles) and depth of the mechanically abraded regions of the RL coating. All plots show $n = 3$ (mean ± SD). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

We designed quick-release medical tape for sensitive skin such that the weakest attachment point is between the backing and adhesive layers, thereby avoiding large stresses and strains on the skin during removal. Field emission scanning electron micrographs of laser-etched and sandpaper-roughened RL-coated backings used in the construction of quick-release medical tape are shown in Fig. 3 *Ai*, *Bi*, and *Ci*. Energy-dispersive spectroscopic analysis shows that for all samples tested, the etched or abraded regions have minimal silicon content (indicating negligible residual siloxane coating) relative to the carbon and oxygen content, indicative of a PET surface. Regions between etchings or abrasions show higher silicon content, indicating the siloxane RL is intact. Representative energy-dispersive spectra from a laser-etched grid sample are shown in Fig. 3*Bii*.

Three-dimensional profilometer images show the microtopography of the quick-release medical tape backing layers (Fig. 3 *Aiii*, *Biii*, and *Ciii*). Approximately 100-μm-wide laser-etched lines (*w*) spaced 500 μm apart (*p*; center to center distance or pitch) running along the width of the RL-coated PET backing provides a modest increase in average and maximum peel adhesion over more widely spaced lines and RL coated PET alone. Average and maximum peel forces of the micropatterned RL-PET backing from the adhesive are in good agreement with the experimental curve fit determined by the macroscale strip peel force data (Fig. 3*A*). The percentage area of exposed PET (*x*) is

calculated as the ratio of the width of the laser-etched lines (115 μm, as measured by profilometry) divided by the spacing of the lines. The length of the line equals the width of the backing and, therefore, cancels out of the equation:

$$x_{lines} = \frac{w}{p}$$

Theoretical peel forces represented by the dashed line were calculated as a function of the percent PET area of the laser etched lines described by the inverse cubic function determined by the best-fit curve to the macroscale strips of RL and PET. Peel-force predictions closely match the experimental results, from which we infer the amount of backing exposed to the adhesive dictates peel force between the backing and adhesive layers. Therefore, patterning at the microscale follows the macroscale trend enabling fine-tuning of the surface area of interaction between the backing and adhesive layers. By elucidating the quantitative relationship between the spatial ordering of adhesive and antiadhesive regions of the backing microtopography, we present an experimentally validated governing relationship. From this experimentally determined relationship, we can accurately tune the peel force of the backing layer to any value between the adhesive force of a strong adhesive and a completely RL-coated antiadhesive backing. We show that the relationship holds when lines are etched in grid form and expect similar results for any spatial ordering of adhesive and antiadhesive backing materials.

Laser-etching square grid lines into RL-coated PET (photographed in Fig. S1) increases the exposure of PET to the adhesive (*x*). Laser-etched lines patterned sequentially closer than 0.5 mm heat the same area of the polymer backing before it has had time to cool, which can warp or melt the backing polymer based on its thermal stability. The percentage PET exposed to the surface can be calculated for the smallest repeat unit, a square, and generalized because of symmetry. Each square has an exposed PET area of twice the width of the line multiplied by the center to center line spacing minus the overlapping portion of the lines at the corners normalized by the area of the square repeat unit:

$$x_{grid\ lines} = \frac{2wp - w^2}{p^2}$$

As with the laser-etched lines, the square gridlines etched into the RL-PET backing produces uniform peel strength. The 1-mm-spaced square gridlines produces peel forces similar to that of the 0.5-mm-spaced lines, because both have similar amounts of exposed PET (Fig. 3*B*). Accordingly, the 0.5-mm laser-etched square grid lines produce a backing adhesion force of approximately double that of the 0.5-mm-spaced lines. The theoretical peel adhesion values closely match the experimental results.

Physical abrasion can also selectively remove the RL coating exposing the underlying PET. A 120-grit (115 μm average particle diameter) and a 240-grit (53 μm average particle diameter) sandpaper-roughened RL-PET backing produced similar levels of adhesion, significantly greater than those achieved by laser etching without causing excessive localized heating. Whereas the grit is more densely packed on the 240-grit sandpaper, the grit layer has greater thickness on the 120-grit sandpaper. Therefore, the 120-grit sandpaper creates deeper and more widely spaced divots than the 240-grit sandpaper (depth profiling shown in Fig. S2), likely leading to similar amounts of PET exposed to the adhesive layer (Fig. 3*C*). Because of its amorphous nature, the acrylate adhesive can readily fill microscale divots enabling adhesion as a function of interfacial contact area. A 400-grit (23 μm average particle diameter) sandpaper exposes a significantly greater fraction of PET than 120- or 240-grit sandpaper (Fig. S2), stabilizing the interface between the backing and adhesive layers and, thus, transitioning the fracture zone to within the adhesive layer. Because the average particle radius of 400-grit
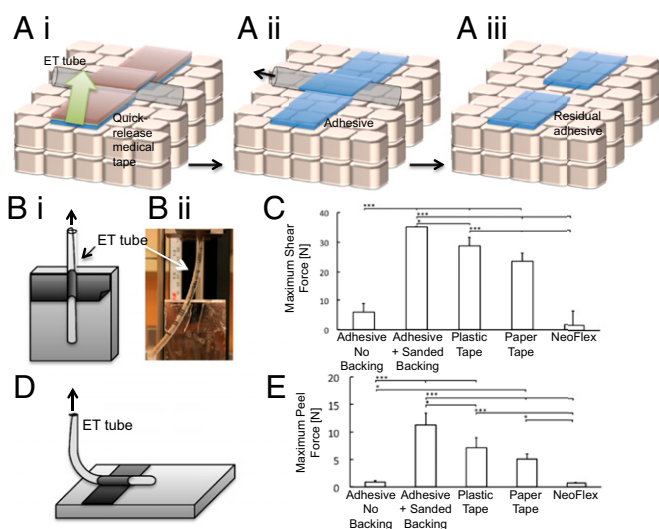
Fig. 4. Quick-release tape affixes medical devices securely and enables effortless removal. (*Ai*) Schematic of quick-release, intact, three-layer medical tape affixing an ET tube to the skin. (*Aii*) Coated backing (backing and intermediary layers) removed by peeling to leave only the residual adhesive layer affixing the ET tube to the skin. (*Aiii*) ET tube pulled from the skin causing cohesive failure of the adhesive layer to release the ET tube, leaving residual adhesive on the skin with a gap where the ET tube was previously affixed. (*Bi*) Scheme of shear force apparatus used to determine maximum fixation of ET tubes. (*Bii*) Following removal of the backing layer, a neonatal ET tube was easily removed from the residual adhesive. This shows that the adhesive layer fails in cohesion with minimal applied shear force once the backing is removed to facilitate rapid release the tube. (*C*) The shear force achieved during ET-tube removal is maximized when the backing layer is in place. The force of removal was less for plastic and paper tapes (likely due to less aggressive adhesives used in these tapes), and very low for NeoFlex. Upon removal of the backing from the RL-PET tape, the maximum shear force drops by 83%. (*D*) Scheme of setup for testing normal adhesion during 90° ET-tube peel. (*E*) Trends in maximum normal adhesion achieved during 90° ET-tube peel testing follow those of shear testing. Removing the backing of the quick-release medical tape leads to a 92% reduction in adhesion normal force. All plots show $n = 3$ (mean ± SD). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

sandpaper (11.5 μm) is an order of magnitude greater than the thickness or the RL coating (0.5–0.8 μm), abrasion readily removes a significant fraction exposing the underlying PET. Thus, use of 400-grit sandpaper led to portions of adhesive remaining on the backing when peeled from stainless steel. Two-dimensional profiles reveal that rms-averaged surface roughness created by sandpaper roughening decreases with decreasing particle size (Fig. S2). Although laser-etched micropatterning creates more regularly spaced features, physical abrasion is a more readily scalable process for creating quick-release medical tapes.

PET is often used as a test backing in medical tape and transfer film construction (12); however, it is nonstandard for use as a commercial medical tape backing. To test how generalizable the approach of micropatterning RL is, the adhesive was removed from a commercially available plastic-backed medical tape that is composed of a proprietary polyethylene–ethylene vinyl acetate (PE-EVA) blend. The adhesive-stripped backing was coated with RL and patterned via sanding to expose regions of the underlying backing. The sanded RL-coated PE-EVA backing showed peel adhesion between the values obtained for RL-coated PE-EVA and PE-EVA alone using the adhesive from the PET experiments, producing a similar trend (shown in Fig. S3). Mechanical abrasion and photothermal ablation can be used alone or in combination to pattern any suitable RL-coated backing to create adhesive and nonadhesive zones at the interface between the backing and adhesive layers, thereby imparting full control over the backing peel strength without substantially reducing shear adhesion.

ET tubes affixed by tape were also peeled at 90° from a polished stainless steel plate to test device fixation in the normal direction (setup shown in Fig. 4D). Intact quick-release tape achieved the highest normal adhesion force, followed by commercial plastic and paper medical tapes, with NeoFlex and the residual adhesive alone demonstrating the lowest forces. After removing the quick-release medical tape backing layer, the residual adhesive exhibits 93% less normal adhesive force than intact quick-release tape facilitating quick, damage-free device removal.

In addition to controlling peel force between the backing and adhesive layers, for quick-release medial tape to perform in a neonatal intensive care setting it must securely affix devices to the skin. With the backing in place, patterned quick-release tapes firmly secured a neonatal ET tube to the skin (Fig. 4Ai) and exhibited stronger shear adhesion than standard medical tapes (Fig. 4 B and C), producing higher average maximum shear force than plastic ($P < 0.05$) and paper tape ($P < 0.001$). Patterned quick-release tape with its backing in place also significantly outperformed tape designed for easy removal from neonates (NeoFlex; $P < 0.001$). Conventional medical tapes also exhibited higher average maximum shear force than NeoFlex ($P < 0.001$). After peel removal of the RL coating and backing, only the adhesive remains fixing the ET tube to the skin (Fig. 4Aii). With only the adhesive securing the ET tube, the ET tube is easily pulled from the skin, leaving a gap in the residual adhesive from where it is removed (Fig. 4 Aiii and Bii). Cohesive failure of the adhesive at the edges of the ET tube requires minimal shear force, unlike when the backing is in place ($P < 0.001$) and compared with common medical tapes ($P < 0.001$). Because of the low adhesive shear strength of NeoFlex tape
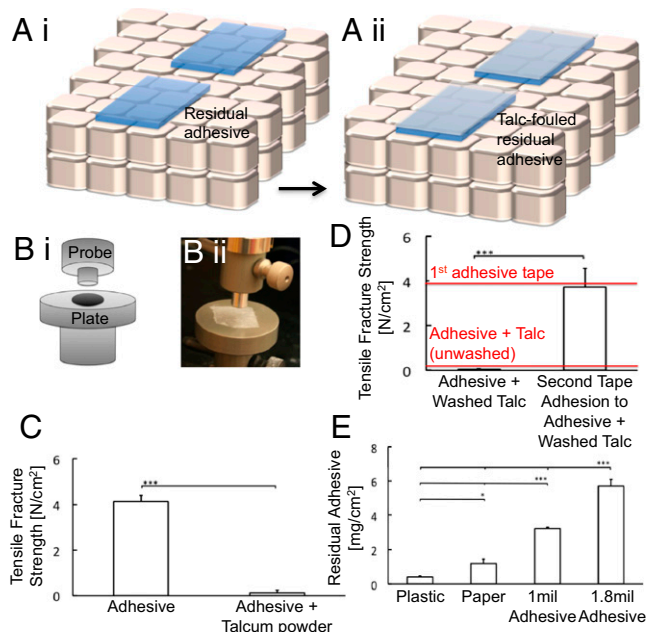

Fig. 5. Talc detackifies residual adhesive. (*Ai*) Residual adhesive from quick-release medical tape on skin after device removal. (*Aii*) Talc-fouled exposed surface, detackifying residual adhesive. (*Bi*) Schematic of the probe tack test. (*Bii*) Talcum "baby" powder–fouled and washed residual adhesive after washing (retains translucence). (*C*) Probe-tack tensile fracture strength is virtually eliminated by fouling with talcum powder ($P < 0.001$). (*D*) Probe tack to talcum powder–coated residual adhesive remains low after washing with water. Adhesion of a second adhesive layer approximates the initial probe-tack adhesion when adhered to the fouled, washed residual adhesive. (*E*) Residual adhesive mass per area for commercial tapes is less than that left by the RL-PET tape; however, the residual adhesive of the RL-PET tape is wholly dependent on the coating thickness and can, therefore, be tailored. All plots show $n = 3$ (mean ± SD). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

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designed for easy removal in a neonatal care setting, the adhesive alone exhibited similar average maximum shear force ($P > 0.05$).

In addition to manually rolling the residual adhesive left by quick-release medical tape on the skin, application of talcum powder can be used to detackify the residual adhesive (Fig. 5A). In particular, talcum powder significantly reduces the tackiness of the residual adhesive, while still providing a surface to which a secondary adhesive can readily adhere at full strength (Fig. 5 $B–D$). Conventional medical tapes often exhibit cohesive failure in the adhesive layer during removal, leading to islands of residual adhesive, especially after long-term wear. When common medical tapes were removed from aluminum foil sheets and compared with quick-release tapes, the residual adhesive mass per square centimeter was on the same order of magnitude (1–10 mg/cm^2; Fig. 5E). Because the acrylate adhesives used in these studies are commonly found on the skin after medical tape removal, no skin irritation is expected from long-term exposure to residual adhesive left by quick-release medical tapes.

Based on our qualitative observations, removal of residual adhesive left by quick-release medical tape can be pushed and rolled to fully remove it, possibly because of increased residual adhesive thickness left by quick-release medical tape. However, pushing and rolling may not be suitable for fragile skin. Leaving residual adhesive on the sensitive skin may be safer than aggressive removal. However, residual adhesive left on the skin by the quick-release medical tape could errantly adhere to other surfaces (e.g., clothing or bedding). Once fouled, the residual adhesive no longer exhibits tack. Additionally, when the excess talc is washed away, a second medical tape can be applied and achieve secure fixation. Therefore, quick-release medical tape design allows for rapid device removal and repositioning.

Discussion

In the case of the quick-release medical tape, once the backing is removed, the cohesion of the chosen adhesive determines the degree of device fixation, making it adjustable without necessarily affecting the adhesive properties. Quick-release medical tape, therefore, functions better in affixing devices than current medical tapes tested while the backing is in place. Once the backing is easily peeled from the quick-release tape, the adhesive layer is left intact with the underlying skin undamaged. In an emergency setting, the backing can be peeled very quickly without imparting significant strain onto the skin. With only the residual adhesive providing fixation, the device can then be easily and quickly removed.

By comparing the maximum shear performance (Fig. 4C) and the backing peel force (Fig. 3), the directional anisotropy of the adhesion between the adhesive and RL-coated backing layers is apparent. Quick-release medical tape provides significant adhesion in shear while the backing is in place, and the same backing exhibits minimal adhesion when peeled from the adhesive layer at 90°. Although standard commercial medical tapes also provide good shear strength, unlike quick-release tapes, they require high peel force and are, therefore, dangerous to remove from sensitive skin.

Separation of the backing layer from the adhesive has enabled the development of a paradigm for dual-adhesive functional quick-release medical tape that protects the underlying surface during tape removal. Micropatterning RL-coated backing materials enables tuning of the peel force to separate the backing layer from the adhesive. Specifically, the surface area of interaction between the backing layer and the adhesive layer correlates well with backing-layer peel force, providing a theoretical framework for determining the optimal balance of adhesive and antiadhesive features to achieve a desired peel strength. Therefore, RL micropatterning can be used to adjust the level of peel adhesion between nearly any backing and adhesive in a controllable, predictable manner, without sacrificing device fixation integrity because of the dual-adhesive functionality and spatial ordering of the composite backing/adhesive interface.

Materials and Methods

To fabricate a triple layer adhesive that would separate between the backing and adhesive layers, 50-μm-thick PET sheets were coated with siloxane-based RL using a Euclid Coating Systems Single Roll Coater to form the backing layer. To cure the two-part, Dow Corning 9106 RL coating, the coated sheets were placed in a drying oven for 5 min at 180 °C. By adjusting the power and cutting speed of a 30-watt VersaLASER VLS 2.3, the RL coating can be selectively etched or the full thickness of the backing material can be cut to any into computer-drawn pattern. The resultant backing strips were then cleaned in 70% ethanol to remove residual particulates.

Adhesive was then applied either by solvent-casting Cytec GELVA GMS 2999 pressure-sensitive adhesive and heating at 60 °C to accelerate solvent evaporation, or a transfer film was formed (Syntac Coated Products) and the preformed, solvent evaporated adhesive layer was physically transferred onto the backing (diagrammed in Fig. S4). To summarize, the PET backing layer (layer 1) was coated with RL (layer 2) and then acrylate adhesive (layer 3) to create triple-layer quick-release medical tapes.

For additional information, see SI Materials and Methods.

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