Polar Opposite Functions of the North American Porcupine Quill and Quill-mimetic Medical Devices

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Statement of purpose: North American porcupines are well known for their specialized quills that are used in self-defense. It has been well documented that it is difficult to remove porcupine quills once the quills are lodged within tissue. However, the forces involved in penetration and pull-out have yet to be described and a comprehensive mechanism remains elusive. Herein we study how the natural quill's geometry enables easy penetration and high tissue adhesion where the barbs specifically contribute to adhesion and unexpectedly, dramatically reduce the force required to penetrate tissue. The dual functions of barbs were reproduced with replica molded synthetic polyurethane (PU) quills. As potential applications, we fabricated quill-mimetic needle and a tissue adhesive patch.

Methods: For the finite element simulation, we model the quill and barbs as a linear elastic material with Young's modulus E = 3.25 GPa and Poisson's ratio $\nu = 0.4$ as determined from uniaxial tension experiments of quill tips. The porcine skin is modeled as a non-linear incompressible material using the inverse Langevin model with an initial shear modulus $\mu = 0.165$ MPa and locking stretch $\lambda_L = 1.81$. We used the quills with a barbed region of 4 mm for the penetration-retraction tests with muscle tissue. The force measurements were performed with the mechanical tester (Model 5540, Instron Corporation). The quills with different length of barbed regions and barbless quills were prepared by sanding off barbs gently.

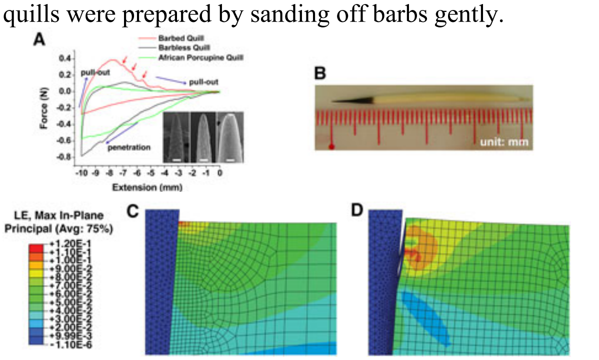

Figure 1. (**A**) Representative force versus extension plots show puncture, penetration, and removal of barbed, barbless, and African porcupine quills from muscle tissue. The scale bars in inset present 100 µm. (**B**) Digital photograph of the North American porcupine quill. (**C, D**) Strain field distribution in skin tissue when a barbless or two-barbed quill is penetrated into tissue, respectively.

Results: Compared with the barbless quill and naturally barbless African porcupine quill, the barbed quill requires less penetration force and work of penetration (Fig. 1A) while minimizing tissue damage. Stress concentrations generated by the barbs during penetration likely stretches or tears tissue fibers locally at the interface of the quill. To visualize the effect of barbs on penetration, we examined the strain distribution in tissue using finite element analysis for a barbless quill and a simplified two-barbed quill (Figs. 1B and C). The analysis revealed that tissue is primarily stretched and deformed by high stress concentrations near the barbs. The local stress concentrations likely reduce the need to deform the entire circumference of tissue surrounding the quill, consequently reducing the penetration force. The length of barbed area at the quill tip is 4 mm from the apex (Fig. 1D). We investigated which barbed regions are critical for penetration and pull-out forces. The 2-4 mm barbed region is the most critical to reduce penetration force. The first 1 mm barbed region independently makes the greatest impact on pull-out force. In addition, there is cooperation between 0-2 mm and 2-4 mm regions to increase pull-out force. We reproduced the dual functions of barbs with synthetic PU barbed quills. We also fabricated quill-mimetic barbed needle, which penetrated into tissue with less force compared to control, and quill-mimetic PU patch as an adhesive (Fig. 2).

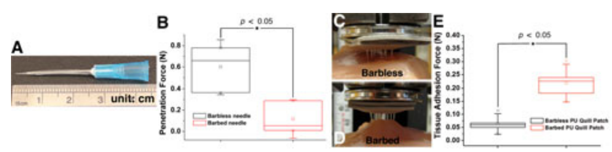

Figure 2. (**A**) Fabricated quill-mimetic needle. (**B**) The forces required to penetrate the fabricated barbed/barbless needles into a model of human skin. (**C, D**) Show the quill-mimetic patches interacting with muscle tissue during the retraction process from muscle tissue. (**E**) The tissue adhesion forces obtained from barbless and barbed PU quill patches (n=5, student *t*-test at the level of 95% significance).

Conclusions: We report how the North American porcupine quill displays a unique geometry that serves two polar opposite functions. In addition to tissue adhesives, these findings should serve as the basis for the development of needles, trocars, and vascular tunnelers where minimizing penetration force is important.

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