BRIEF COMMUNICATIONS

Early Neolithic tradition of dentistry

Flint tips were surprisingly effective for drilling tooth enamel in a prehistoric population.

Prehistoric evidence for the drilling of human teeth *in vivo* has so far been limited to isolated cases from less than six millennia ago[1–3]. Here we describe eleven drilled molar crowns from nine adults discovered in a Neolithic graveyard in Pakistan that dates from 7,500–9,000 years ago. These findings provide evidence for a long tradition of a type of proto-dentistry in an early farming culture.

The site of Mehrgarh in Baluchistan lies along the principal route connecting Afghanistan to the Indus valley. After intermittent occupations by hunter–gatherers, Mehrgarh's subsistence economy shifted to the cultivation of barley and wheat, cotton domestication and cattle breeding[4]. Diachronic archaeological evidence records an increasingly rich cultural life, with technological sophistication based on diverse raw materials. Excavation of the Neolithic cemetery known as MR3 yielded more than 300 graves created over a 1,500-year time span[4].

We identified four females, two males and three individuals of unknown gender that between them had a total of eleven drilled permanent crowns (for details, see supplementary information). Drilled teeth were evident in both jaws (four in the maxilla; seven in the mandible) and exclusively in the first (four specimens) or second (seven specimens) permanent molars. Except for one located on the distal–buccal cervix of a lower first molar, the holes were bored into enamel or secondary dentine on the occlusal surfaces. The holes are 1.3–3.2 mm in diameter and angled slightly to the occlusal plane, with a depth of between 0.5 and 3.5 mm.

Light microscopy, scanning electron microscopy and microtomography revealed cavity shapes that were conical, cylindrical or trapezoidal (Fig. 1; and see supplementary information). They also showed concentric ridges preserved on some walls that had been left by the drilling tool. The teeth of at least one individual reveal that the procedure involved not just removal of the tooth structure by the drill, but also subsequent micro-tool carving of the cavity wall by either the operator or the patient. In all cases, marginal smoothing confirms that drilling was performed on a living person who continued to chew on the tooth surfaces after they had been drilled.

Complete dentition for the 11 specimens is not preserved, so the incidence per jaw cannot be determined. However, one individual had three drilled teeth and another had a tooth that had been drilled twice. Four teeth show signs of decay associated with the hole, indicating that the intervention in some cases could have been therapeutic or palliative. But as caries can exist in individuals in the absence of drilling, and drilling may be done in individuals without caries, the motive for the early Neolithic dental procedure described here is unclear. Aesthetic functions[5] can be ruled out because of the deep placement in the jaw. The perforations exposed sensitive tooth structure, so some type of filling may have been placed in the cavity; however, no evidence survives to confirm this.

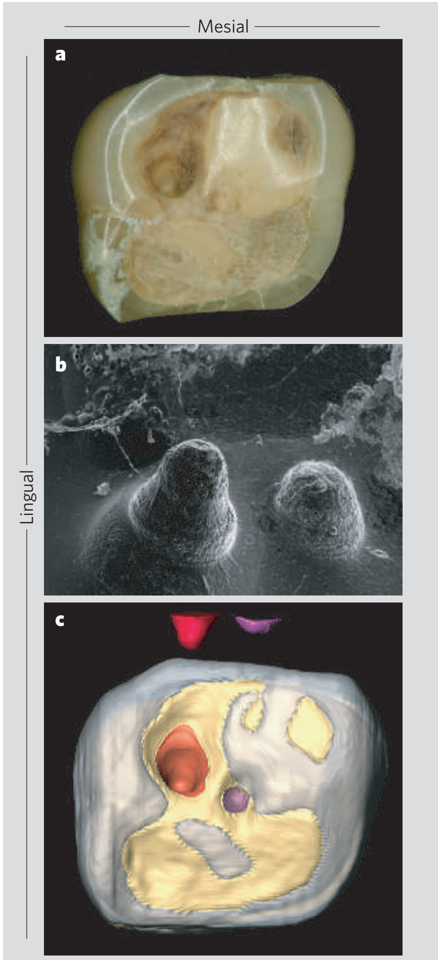

Figure 1 | Maxillary left second molar from an adult male (MR3 90) from Neolithic Mehrgarh. There are two *in vivo* perforations on the occlusal surface made by a drilling tool that was probably equipped with the same flint head. **a,** The larger, mesio–lingual perforation has a maximum diameter of 1.6 mm; the second, at the centre of the crown, has a maximum diameter of 1.3 mm. **b,** Scanning electron micrograph of their negative replicas, showing that both perforations are slightly inclined mesio–distally and have a similar general shape. The larger perforation is also deeper (1.5 compared with 0.7 mm). **c,** A microtomographic three-dimensional reconstruction of the tooth, with positive virtual casts (top) of the two perforations (for methods, see supplementary information). The minimum volume of removed enamel and dentine in the mesio–lingual perforation (red) is 1.8 mm^3; the minimum volume of removed enamel for the smaller perforation (violet) is 0.3 mm^3. Scale bars: **a**, 2.2 mm; **b**, 1 mm; **c**, 2 mm.

Whatever the purpose, tooth drilling on individuals buried at MR3 continued for about 1,500 years, indicating that dental manipulation was a persistent custom. After 6,500 yr BP, the practice must have ceased, as there is no evidence of tooth drilling from the subsequent MR2 Chalcolithic cemetery, despite the continuation of poor dental health[6].

At Neolithic Mehrgarh, flint drill heads occur in the lithic assemblages associated with beads of bone, steatite, shell, calcite, turquoise, lapis lazuli and carnelian[7]. Using models of these drill tips, we reconstructed a method for drilling based on the ethnographic literature[8] and found that a bow-drill tipped with a flint head required less than one minute to produce similar holes in human enamel. Presumably, the know-how originally developed by skilled artisans for bead production was successfully transferred to drilling of teeth in a form of proto-dentistry.

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PARASITOLOGY

Parasite survives predation on its host

As prisoners in their living habitat, parasites should be vulnerable to destruction by the predators of their hosts. But we show here that the parasitic gordian worm *Paragordius tricuspidatus* is able to escape not only from its insect host after ingestion by a fish or frog but also from the digestive tract of the predator. This remarkable tactic enables the worm to continue its life cycle.

The induced suicide of crickets infected by gordian worms is one of the best known examples of parasite manipulation of host behaviour[1]. Adult gordian worms are free-living in water, where they mate as a knotted mass of multiple individuals. Emergence from the host occurs only after the cricket enters the water (for movie, see supplementary information) and may take as long as 10 min owing to the large size of the worm[1]. During this time, the cricket is active at the surface and attractive to aquatic predators such as fish and frogs (F.T., unpublished observations). Death of the worm would be expected to result from generalist predation upon the host at this stage unless the parasite were capable of an antipredator response.

Few parasites have their own predators, although they are victims of those of their hosts. Predation upon a host may shape parasite life history in two important ways. First, increased predation may select for increased parasite virulence[2,3]: for example, parasite development can speed up to minimize the period of host occupancy[4]. Increased virulence may also take the form of manipulating the host's behaviour[5], for example to remove it from sources of predation[6,7]. Second, predation may affect parasite life history if the predator becomes incorporated into the life cycle[8–10].

We investigated the response of gordian worms to predation on their host. Under laboratory conditions, we found that crickets that harboured or were expelling gordian worms were often eaten by generalist predators — fish (trout (*Oncorhynchus mykiss*), perch (*Lepomis gibbosus*), bass (*Micropterus salmoides*)) and frogs (*Rana erythraea*). In none of the 477 predation events that we observed did the predator regurgitate the cricket. Remarkably, the worm escaped predation by wriggling out of the mouth, nose or gills of the predator that had consumed its host (Fig. 1). This escape was recorded from trout (18%, $n = 141$), bass (26%, $n = 292$), perch (22%, $n = 27$) and frogs (35%, $n = 17$) (for methods, see supplementary information).

The mean time until full emergence was 8.6 min (518 ± 208 s, $n = 72$). The maximum time was 28 min, when the predator repeatedly tried to swallow the worm while it was escaping. If a worm did not start to emerge from the mouth, gills or nose within 5 min, it failed to escape — dying, presumably, in the hostile environment of the predator's stomach. To our knowledge, this escape response by a gordian worm is the first example of a parasite or any organism surviving predation in this way.

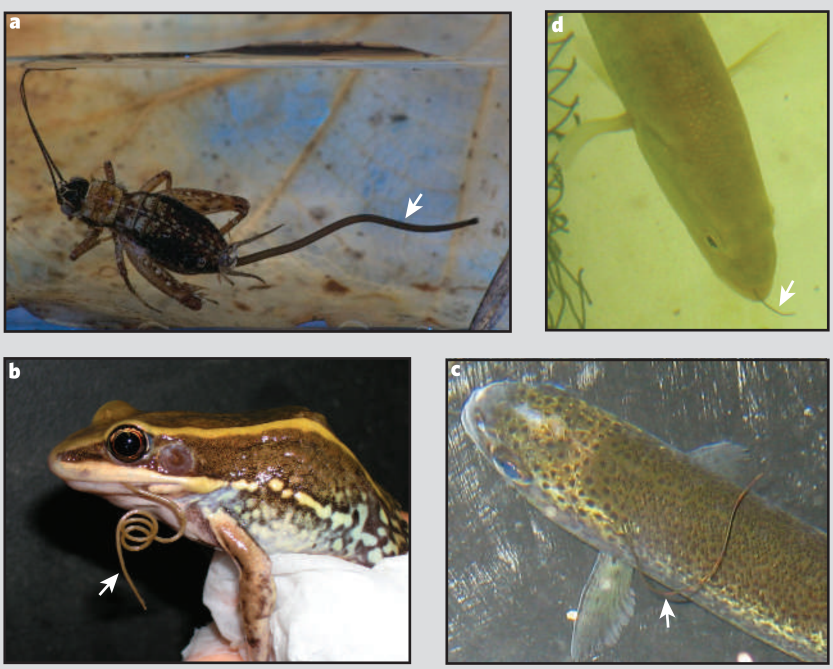

Figure 1 | Escape of parasitic gordian worms from their insect host and from the host's predators. **a,** Gordian worm (arrow) emerging from a host cricket; **b–d,** gordian worms (arrows) emerging from a frog (**b**), a trout (**c**) and a bass (**d**) after ingestion of the host insect by these predators. For movies, see supplementary information.

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