adjust the sex of their offspring in response to environmental conditions[1,2,4,10], suggesting that the dimensionless approach could be applied widely. More generally, our results demonstrate the usefulness of the dimensionless approach, in that it can allow quantitative tests of evolutionary theory in cases where the difficulty of measuring the underlying trade-offs has constrained previous tests to merely qualitative status.

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Ancient materials

Analysis of a pharaonic embalming tar

Details of mummification techniques used in dynastic Egypt have emerged from writings in subsequent ancient texts, in which the application of oils (*kedros, cedrium*) derived from the cedar tree have been described by Herodotus (490–425 BC)[1] and by Pliny the Elder (AD 23/24–79)[2]. But scholars have since argued that these products were prepared from juniper trees and not from cedar[3] — an assertion that is widely accepted by Egyptologists[4] but which has never been verified by chemical analysis. Here we use gas chromatography to analyse the constituents of a sample of unused entombed embalming material from 1500 BC at a site in Deir el-Bahari, Egypt, and find that its components probably originated from the cedar tree. We also identify one component, guaiacol, as having notable preservative properties.

In ancient Egypt, the deceased were mummified in the hope that this would ensure their eternal survival. The process included removal of the internal organs, followed by desiccation and embalming of the carcass[5,6]; occasionally cosmetics were applied[7] as a wealth of different compounds. Active enzymes have recently been isolated from embalmed bones from pharaonic Egypt[8].

We prepared a methanolic extract from unused embalming material (Fig. 1) found near the mummy '*Saankh-kare*', from the eighteenth dynasty, 1500 BC, at Deir el-Bahari. Gas chromatography of the extract showed no evidence of diterpenoid or triterpenoid resin components, but phenolic compounds (such as cresols, xylenols, guaiacols (2-methoxyphenols)), naphthalenes and azulenes were present (see supplementary information).

The phenolic and naphthalene derivatives probably originated from smouldering wood, with the methoxyphenols arising from lignin-degradation products that resulted from the pyrolysis of soft coniferous wood[9]. Dimethoxyphenols (syringols), on the other hand, are additionally formed by heating the hard wood of deciduous trees[10]. The presence of guaiacols without syringols in the embalming material strongly supports an origin from coniferous wood.

The brown embalming resin also contains sesquiterpenoid components, which are normally found in a fluid known as 'cedar oil'. This oil is prepared by extraction with organic solvents of wood from *Cedrus atlantica* and also includes junipene, cadalene, cadinatriene (calamene), cuparene and α-curcumene. Given the prevalence in the resin of guaiacols from coniferous wood-tar oils, our findings indicate that the embalming material was prepared from cedar trees.

The liquid probably originated from the water-containing fraction that is exuded before the tar from dry-distilled cedar wood. In his *Naturalis Historia*, Pliny the Elder[2] describes the technology: "*The wood of the tree is chopped up and put into ovens and heated by means of a fire packed all round outside. The first liquid that exudes flows like water down a pipe; in Syria this is called 'cedar-juice'* [in Latin: *cedrium*], *and it is so strong that in Egypt it is used for embalming the bodies of the dead*." The application of a liquid cedar product is also described by Herodotus[1].

There is an unfortunate tradition of confusion between cedar and juniper trees, which has led to the erroneous assignment of Pliny's *cedrium*. In today's terminology as well as in ancient times, some juniper trees that are not cedar are still called cedar — for example, the American red cedar (*Juniperus virginiana)* and the Mediterranean 'little cedar' (*Juniperus oxycedrus*). In this context, our comparative investigations show that the oils or tars from juniper trees contain high amounts of cedrol or cedrene, respectively, neither of which was found in the *Saankh-kare* embalming material.

The surfaces of mummies embalmed with liquid tars or other liquid resinous materials are essentially free of contaminating microorganisms. The sealing effect of the embalming agents on the bone surface preserves the enzyme alkaline phosphatase inside for thousands of years[8]. We therefore tested the contribution of phenolic derivatives, which in the embalming agent originate from a smouldering process, and monoterpenes, which occur naturally in resinous balm, to this biochemical conservation process.

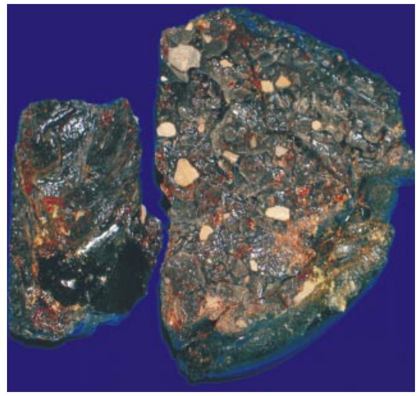

Figure 1 Unused embalming material ('*cedrium*') entombed with the mummy *Saankh-kare* (from 1500 BC and cemetery field 26225 at Deir el-Bahari in Egypt), at present located at the Egyptian Art Department of the Metropolitan Museum of Art, New York. The dark-coloured parts are organic resin; the pink and lighter-coloured inclusions orginate from mineral-based impurities.

Guaiacol, *p*-cymene, limonene and α-pinene were tested for their effect on preserving alkaline phosphatase activity in a model embalming process, in which porcine bones were coated with one of these compounds for 35 days at room temperature. We found that guaiacol was the most effective preservative as the enzyme's specific activity was 12 times higher than that in an untreated bone control and exceeds the activity recovered from bones treated with monoterpenes (cymene has no effect; α-pinene and limonene seem to promote enzyme degradation) or with disinfectants such as phenols (see www.pci.chemie.uni-tuebingen.de/weser/supp_info.htm).

We conclude that liquid tars in general are most efficient in the mummification process. The methyl- and ethylguaiacol identified in the *cedrium* of Deir el-Bahari are characteristic representatives of wood creosotes (from the Greek '*kreas*', or flesh, and '*soter*', preserver). Creosotes are nowadays used for rapid smoke-drying of meat. Thus, these outstanding conserving properties confirm the statements of Herodotus and Pliny that a "strong" liquid was used for embalming in ancient Egypt.

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