

Vestigial Biological Structures: A Classroom-Applicable Test of Creationist Hypotheses

RECOMMENDED
FOR AP Biology

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ABSTRACT

Lists of vestigial biological structures in biology textbooks are so short that some young-Earth creationist authors claim that scientists have lost confidence in the existence of vestigial structures and can no longer identify any verifiable ones. We tested these hypotheses with a method that is easily adapted to biology classes. We used online search engines to find examples of 21st-century articles in primary scientific literature in which biological structures are identified as vestigial. Our results falsify these creationist hypotheses and show that scientists currently identify many structures as vestigial in animals, plants, and single-celled organisms. Examples include not only organs but also cells, organelles, and parts of molecules. Having students repeat this study will give them experience with hypothesis testing, introduce them to primary scientific articles, and further their education on vestigial structures.

Key Words: Vestigial structures; vestigial organs; evolution; creationism; primary scientific literature.

○ Introduction

Many organisms possess biological structures that are recognizable as degenerate versions of their homologs in related organisms and that do not perform the functions that those homologs perform. For example, degenerate eyes in blind cave fishes and cave salamanders are useless for vision (Eigenmann, 1900), and degenerate limbs in numerous lizard species are useless for locomotion (Moch & Senter, 2011). Such degenerate structures are called “vestigial structures” because they are vestiges (remnants) of ancestral structures. Biologists recognize vestigial structures as evidence for biological evolution (Starr & Taggart, 2004; Reece et al., 2011). For example, blind cave fishes and salamanders arguably have eyes only because they inherited them from sighted ancestors.

Until recently the human and ape appendix has been considered a vestigial organ, a remnant of a much larger ancestral cecum. A cecum is a side branch of the large intestine that houses bacteria

that break down cellulose, enhancing the digestion of plant matter in herbivorous mammals (Kardong, 2011). However, an anatomical study of primates showed that the appendix of humans and apes is not a remnant of a cecum but is instead an evolutionarily new structure with no homolog in lower primates (Scott, 1980). It appears to function as a protective reservoir for beneficial bacteria that inhabit the colon, a microbial “Noah’s ark” from which beneficial bacteria can repopulate the colon if a disease decimates them (Bollinger et al., 2007).

The recognition of the appendix as vestigial ceased not because it has a function but because it is a newly evolved structure instead of a vestige of an ancestral structure. A structure does not have to be useless or functionless to be a vestige. Even so, scientists generally hesitate to use the term “vestigial” for a structure unless it has lost its most salient previous function. For example, the degenerate pelvises of whales currently function as anchors for reproductive structures but are considered vestigial because they have lost their previous function as anchors for hindlimbs that are used in locomotion (Simões-Lopes & Gutstein, 2004). Likewise, the degenerate ink glands of certain marine snails store algal pigments but are considered vestigial because they have lost their previous function as organs of ink production (Prince & Johnson, 2006).

Anti-evolution authors in the young-Earth creationist (YEC) camp have long insisted that all structures previously identified as vestigial are actually misidentified as such (e.g., Morris, 1974; Koop & Schaeffer, 1987; Bergman & Howe, 1990; Bergman, 2000; Menton, 2010). According to the YEC argument, no truly vestigial biological structures exist. Rather, in each case, the structure

is functional but its function was unknown when it was labeled as vestigial. Such authors fail to understand that a structure can have a function and yet be a vestige. Nevertheless, some of these YEC authors have noticed something that is worth noticing: Lists of vestigial structures in biology textbooks have dwindled through the

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decades. These authors use this as evidence that scientists have lost confidence in the existence of vestigial structures or that scientists cannot find more examples of valid vestigial structures (Koop & Schaeffer, 1987; Bergman & Howe, 1990; Bergman, 2000). As one YEC author puts it, “vestigial organs...have now been thoroughly discredited” (Bergman, 2010, p. 63).

Indeed, lists of vestigial biological structures in current biology textbooks are usually quite short, with only one to three examples (e.g., Starr & Taggart, 2004; Reece et al., 2011). This is the case even in textbooks for evolution classes (e.g., Ridley, 2004; Kardong, 2008), one of which does not mention vestigial structures at all (Volpe & Rosenbaum, 2000). It is therefore worth testing the YEC hypotheses that biologists have lost confidence in the existence of vestigial structures and that more examples than those in short textbook lists cannot be found. Both hypotheses make the same prediction: that a review of recent primary scientific literature will find only a small number of examples (or none) of biological structures that are identified as vestigial. This is because scientists primarily communicate via primary literature (technical journals, etc.), not textbooks. Here, we report a test of these YEC hypotheses.

The test described below is one that can be employed as an assignment in a biology class to serve three purposes that are important for science students. First, it involves students in hypothesis testing, which gives them experience with scientific method. Second, it introduces students to primary scientific literature, so that they can see firsthand the ultimate sources of the information that ends up in textbooks and in secondhand reports in popular science magazines. Third, it expands their education on vestigial structures beyond the meager information found in textbooks. All three goals were in fact attained when this test was performed in a class taught by one of us (Senter), in which the rest of us were graduate students.

○ Methods

We used the search terms “vestigial” and “vestige” to search online databases of primary scientific articles such as JSTOR (<http://www.jstor.org>) and Science Direct (<http://www.sciencedirect.com>) for examples of articles in which biological structures are explicitly identified as vestigial. We counted such identifications only if the following five criteria were met: (1) The authors’ wording indicates that they themselves consider the structure vestigial and are not merely citing previous opinions on vestigiality. (2) The authors use the word “vestigial” or “vestige,” not just a synonym (e.g., “rudimentary” or “reduced”). (3) The authors are not describing a rare developmental anomaly. (4) The organism with the vestigial structure is extant. (5) The vestigial structures are not just mentioned in passing but are important to the main focus of the article. To avoid the appearance of “stacking the deck,” we did not use any articles for which any of us was an author.

We used only articles published in the 21st century, to ensure that the identification of a structure as vestigial is recent enough to be considered current. We did not use articles from the year 2000, because that is actually the last year of the 20th century.

○ Results

In 21st-century articles from primary scientific journals, we found enough examples of biological structures that scientists identify as

vestigial to place 64 entries in Table 1. Several of these entries include multiple species or supraspecific taxa. This falsifies the YEC hypotheses that scientists have lost confidence in the existence of vestigial biological structures and that scientists cannot find more than a few examples of vestigial biological structures in nature.

○ Discussion

To make our results more useful to others, we have included information on function in Table 1. A few vestigial structures are explicitly recognized as entirely useless in primary scientific literature (Table 1), but most are not.

It is probable that we have missed numerous examples of biological structures that scientists currently consider vestigial. This is because the online search engines cannot find every single scientific article published in the 21st century, because we examined no primary scientific literature from sources other than journal articles, and because we used only English-language articles. Table 1, therefore, should not be considered a complete list, and the absence of a structure therein does not necessarily mean that scientists do not currently consider it vestigial. Furthermore, we did not include the numerous examples of vestigial structures recognized in fossil taxa (e.g., Senter, 2010). These facts, in addition to the fact that Table 1 contains a plethora of examples despite its incompleteness, show that biological structures that scientists currently consider vestigial are common, not rare or nonexistent.

As Table 1 shows, some body parts are particularly prone to vestigiality in certain taxa or in organisms in certain ecological niches. For example, vestigial reproductive structures are common in plants. Vestigial limbs are common in lizards. Vestigial eyes are common in burrowing vertebrates. Vestigial mitochondria are common in microbes that inhabit anoxic environments.

Our results show that scientists recognize vestigiality at numerous levels of biological organization in addition to the organ level. In some cases, a major bodily region is vestigial (e.g., the abdomen of a barnacle; Blin et al., 2003). Structures smaller than organs can also be vestigial. Vestigial organelles have been identified in unicellular organisms (e.g., vestigial mitochondria in several species [Regoes et al., 2005] and vestigial chloroplasts in others [Sekiguchi et al., 2002]). Even parts of molecules can be considered vestigial. Researchers have recently identified vestigial genes in whales (McGowen et al., 2008) and a vestigial region in antibody molecules of wobbegong sharks (Streltsov et al., 2004).

It is rare for biology textbooks to mention vestigial structures other than organs and to list more than three examples. We therefore hope that our compilation in Table 1 will be useful to educators who wish to supplement meager textbook information with further examples. We also recommend that longer lists of vestigial structures be added to biology textbooks, to counter the YEC hypotheses that are falsified here.

Our study is easily adapted to biology classes as an assignment. If students are assigned to find a certain number of publications on vestigial structures in primary scientific literature, they need only be taught how to enter the term “vestigial” or “vestige” in an online search engine and to recognize primary scientific articles (e.g., by the presence of an abstract). The experience and knowledge gained during such an exercise would be a valuable addition to a student’s biological education.

Table 1. Examples of biological structures that scientists have identified as vestigial in primary scientific journal articles published in the 21st century. N = no function listed by author(s). U = useless structure according to author(s).

Taxon	Structure	Structure's Function in Unreduced State	Structure's Function in Vestigial State	Reference(s)
Unicellular Organisms				
Amoebozoa				
<i>Entamoeba histolytica</i>	mitochondria	ATP synthesis	N	Regoes et al., 2005
Apicomplexa				
<i>Cryptosporidium parvum</i>	mitochondria	ATP synthesis	N	Regoes et al., 2005
<i>Plasmodium falciparum</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
<i>Toxoplasma gondii</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
Diplomonadida				
<i>Giardia lamblia</i>	mitochondria	ATP synthesis	Fe-S cluster synthesis	Regoes et al., 2005
Euglenozoa				
<i>Astasia longa</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
Fungi				
<i>Trachipleistophora humanis</i>	mitochondria	ATP synthesis	N	Regoes et al., 2005
Heterokontophyta				
<i>Anthophysa vegetans</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
<i>Blastocystis humanis</i>	mitochondria	ATP synthesis	N	Regoes et al., 2005
<i>Ciliophrys infusionum</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
<i>Pteridomonas danica</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
<i>Paraphysomonas</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
<i>Spumella</i>	chloroplast	photosynthesis	N	Sekiguchi et al., 2002
Multicellular Organisms				
Plantae				
some Arecoideae (a subfamily of palms)	male flowers	pollen production	N	Ortega-Chávez & Stauffer, 2011
<i>Gethyum</i> and <i>Gilliesia</i> (South American alliioids)	stamens	pollen production	N	Rudall et al., 2002
<i>Schiedea</i> (Hawaiian schiedeas)	stamens	pollen production	N	Golonka et al., 2005
<i>Consolea spinosissima</i> (a cactus)	androecium [in female plants]	pollen production	N	Strittmatter et al., 2002
<i>Consolea spinosissima</i> (a cactus)	gynoecium [in male plants]	sperm reception; ovule and fruit production	N	Strittmatter et al., 2002
<i>Fragaria virginiana</i> (strawberry)	stamens	pollen production	N	Ashman, 2003
<i>Nemophila menziesii</i> (Baby Blue-eyes)	anthers	pollen production	N	Gomez & Shaw, 2006
<i>Penstemon centranthifolius</i> (Scarlet Bugler) and <i>P. rostriflorus</i> (Beakflower Penstemon)	stamen	pollen production	U	Walker-Larsen & Harder, 2001

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Table 1. continued

Taxon	Structure	Structure's Function in Unreduced State	Structure's Function in Vestigial State	Reference(s)
<i>Penstemon ellipticus</i> (Rocky Ledge Penstemon)	stamen	pollen production	increases duration of pollinators' visits by hindering nectar access	Walker-Larsen & Harder, 2001
<i>Penstemon palmeri</i> (Palmer's Penstemon)	stamen	pollen production	acts as a lever that increases stigma contact with pollinator	Walker-Larsen & Harder, 2001
<i>Epifagus americana</i> (Beechdrops)	chloroplasts	photosynthesis	N	Sekiguchi et al., 2002
Bryozoa				
Calloporidae (a bryozoan family)	ooecium	protects brood chamber	N	Ostrovsky et al., 2006
Mollusca				
<i>Dolabifera dolabifera</i> (a sea hare)	ink gland	defensive ink production	algal pigment storage	Prince & Johnson, 2006
<i>Octopus vulgaris</i> (common octopus)	shell	external protection	N	Napoleão et al., 2005
Teuthida (squid)	phragmocone	buoyancy	muscle and fin attachment	Arkhipkin et al., 2012
Arthropoda				
Cirripedia (barnacles)	abdomen	multiple functions	N	Blin et al., 2003
<i>Carabus solieri</i> (a ground beetle)	hind wings	flight	U	Garnier et al., 2006
Formidicae (ants) [workers]	spermathecae	sperm storage	N	Bowsher et al., 2007; Gotoh et al., 2013
Formicidae [workers of most species]	wing imaginal discs	wing production	N	Bowsher et al., 2007
<i>Diacamma</i> (a genus of wingless ants) [workers]	wings	flight	social display of reproductive status	Miura, 2005
<i>Apis cerana</i> (eastern honeybee) and <i>A. mellifera</i> (European honeybee) [workers]	spermathecae	sperm storage	N	Gotoh et al., 2012
Lepidoptera larvae (caterpillars)	crop	food storage	defensive regurgitation	Grant, 2006
Chondrichthyes				
<i>Orectolobus maculatus</i> (wobbegong shark)	complementarity-determining region of IgNAR antibody	adhesion to antigen	N	Streltsov et al., 2004
Actinopterygii				
Actinopterygii	vertebral arches of posterior tail	muscle attachment	N	Bensimon-Brito et al., 2012
Acipenseriformes (paddlefishes and sturgeons)	pulmonary artery	blood transport to gas bladder	blood transport elsewhere	Longo et al., 2013

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Table 1. continued

Taxon	Structure	Structure's Function in Unreduced State	Structure's Function in Vestigial State	Reference(s)
<i>Astyanax mexicanus</i> (blind cavefish)	eyes	vision	regulation of circadian rhythms	Espinasa & Jeffery, 2006; Franz-Odenaal & Hall, 2006; Yoshizawa & Jeffery, 2008
<i>Echidna nebulosa</i> (snowflake moray) and <i>Muraena retifera</i> (reticulate moray)	pectoral girdle	support for pectoral fin	N	Mehta & Wainwright, 2007
Actinistia				
<i>Latimeria</i> (coelacanth)	lung	gas exchange	N	Longo et al., 2013
<i>Latimeria</i>	pulmonary vein	blood transport from lung to heart	N	Longo et al., 2013
Amphibia				
<i>Plethodon cinereus</i> (red-backed salamander) and <i>Eurycea</i> (brook salamanders)	fourth epibranchial	gill support	N	Kerney et al., 2012
Sirenidae (legless salamanders)	pectoral girdle	forelimb support	N	Bejder & Hall, 2002
<i>Gegenophis ramswamii</i> (a caecilian)	fourth epibranchial	gill support	N	Müller et al., 2005
Squamata				
Pygopodidae (flap-footed lizards)	hindlimbs	locomotion	N	Brandley et al., 2008
<i>Ophisaurus apodus</i> (European legless lizard)	hindlimbs	locomotion	N	Bejder & Hall, 2002; Brandley et al., 2008
<i>Bipes</i> (a genus of worm lizard)	pelvic girdle	hindlimb support	N	Kearney, 2002
<i>Bipes</i>	hindlimbs	locomotion	N	Kearney, 2002
<i>Rhineura floridana</i> (Florida worm lizard)	eyes	vision	N	Kearney et al., 2005
<i>Rhineura floridana</i>	jugal bone	forms lower border of eye socket	N	Kearney et al., 2005
<i>Blanus</i> (a genus of worm lizards)	hindlimbs	locomotion	N	Kearney, 2002
<i>Feylinia</i> (a skink genus)	sternum	forelimb muscle attachment	N	Kearney, 2002
<i>Jarujinia bipedalis</i> (a skink species)	forelimbs	locomotion	N	Chan-ard et al., 2001
some Serpentes (snakes)	hindlimbs	locomotion	N	Kearney, 2002; Brandley et al., 2008
Aves				
Apterygidae (kiwis), Casuariidae (cassowaries), and Dromaiidae (emus)	wings	flight	U	Maxwell & Larsson, 2007

Table 1. continued

Taxon	Structure	Structure's Function in Unreduced State	Structure's Function in Vestigial State	Reference(s)
Mammalia				
Cetacea (whales)	pelvic girdle	braces hindlimb against vertebral column	support for reproductive organs	Bejder & Hall, 2002; Simões-Lopes & Gutstein, 2004
Mysticeti (baleen whales)	hindlimbs	locomotion	N	Bejder & Hall, 2002
Odontoceti (toothed whales)	olfactory receptor subgenomes	genes for olfactory receptors	N	McGowen et al., 2008
<i>Monodon monoceros</i> (narwhal)	molariform teeth	food processing	U	Nweeia et al., 2012
Felidae (cat family)	clavicle	braces scapula against sternum	N	Hartstone-Rose et al., 2012
<i>Mus musculus</i> (house mouse)	incisor tooth bud	production of incisor	N	Peterková et al., 2002, 2006
<i>Spalax ehrenbergi</i> (Middle East blind mole rat)	retina	image formation	regulation of circadian rhythms	Zubidat et al., 2010
Primates (primates)	Harderian gland	eye socket lubrication	N	Rehorek & Smith, 2006
<i>Perodicticus potto</i> (potto)	index finger	prehension	N	Tague, 2002
<i>Ateles geoffroyi</i> (Geoffroy's spider monkey) and <i>Colobus guereza</i> (mantled guereza)	thumb	prehension	N	Tague, 2002
Catarrhini (humans, apes, and Old World monkeys)	vomer nasal organ	pheromone reception	N	Liman & Innan, 2003; Zhang & Webb, 2003
<i>Homo sapiens</i> (humans)	sinus hair muscle	whisker movement	N	Tamatsu et al., 2007

References

- Arkhipkin, A.I., Bizikov, V.A. & Fuchs, D. (2012). Vestigial phragmocone in the gladius points to a deepwater origin of squid (Mollusca: Cephalopoda). *Deep-Sea Research I*, 61, 109–122.
- Ashman, T.-L. (2003). Constraints on the evolution of males and sexual dimorphism: field estimates of genetic architecture of reproductive traits in three populations of gynodioecious *Fragaria virginiana*. *Evolution*, 57, 2012–2025.
- Bejder, L. & Hall, B.K. (2002). Limbs in whales and limblessness in other vertebrates: mechanisms of evolutionary and developmental transformation and loss. *Evolution and Development*, 4, 445–458.
- Bensimon-Brito, A., Cancela, M.L., Huisseune, A. & Witten, P.E. (2012). Vestiges, rudiments and fusion events: the zebrafish caudal fin endoskeleton in an evo-devo perspective. *Evolution and Development*, 14, 116–127.
- Bergman, J. (2000). Do any vestigial organs exist in humans? *Creation Ex Nihilo Technical Journal*, 14, 95–98.
- Bergman, J. (2010). *Inherit the Wind: a lesson in distorting history*. *Answers Research Journal*, 3, 61–69.
- Bergman, J. & Howe, G. (1990). "Vestigial Organs" Are Fully Functional. Kansas City, MO: Creation Research Society Books.
- Blin, M., Rabet, N., Deutsch, J.S. & Mouchel-Vielh, E. (2003). Possible implication of Hox genes *Abdominal-B* and *Abdominal-A* in the specification of genital and abdominal segments in cirripedes. *Development Genes and Evolution*, 213, 90–96.
- Bollinger, R.R., Barbas, A.S., Bush, E.L., Lin, S.S. & Parker, W. (2007). Biofilms in the large bowel suggest an apparent function of the human vermiform appendix. *Journal of Theoretical Biology*, 249, 826–831.
- Bowsher, J.H., Wray, G.A. & Abouheif, E. (2007). Growth and patterning and evolutionarily dissociated in the vestigial wing discs of workers of the red imported fire ant, *Solenopsis invicta*. *Journal of Experimental Zoology B*, 308B, 769–776.
- Brandley, M.C., Huelsenbeck, J.P. & Wiens, J.J. (2008). Rates and patterns in the evolution of snake-like body form in squamate reptiles: evidence for repeated re-evolution of lost digits and long-term persistence of intermediate body forms. *Evolution*, 62, 2042–2064.
- Chan-ard, T., Makchai, S. & Cota, M. (2001). *Jarujinia*: a new genus of lygosomine lizard from central Thailand, with a description of one new species. *Thailand Natural History Museum Journal*, 5, 17–24.
- Eigenmann, C.H. (1900). Degeneration in the eyes of the cold-blooded vertebrates of the North American caves. *Science*, 11, 492–503.
- Espinasa, L. & Jeffery, W.R. (2006). Conservation of retinal circadian rhythms during cavefish eye degeneration. *Evolution and Development*, 8, 16–22.
- Franz-Odenaal, T.A. & Hall, B.K. (2006). Modularity and sense organs in the blind cavefish, *Astyanax mexicanus*. *Evolution & Development*, 8, 94–100.

- Garnier, S., Gidaszewski, N., Charlot, M., Rasplus, J.-Y. & Alibert, P. (2006). Hybridization, developmental stability, and functionality of morphological traits in the ground beetle *Carabus solieri* (Coleoptera, Carabidae). *Biological Journal of the Linnean Society*, 89, 151–158.
- Golonka, A.M., Sakai, A.K. & Weller, S.G. (2005). Wind pollination, sexual dimorphism, and changes in floral traits of *Schiedea* (Caryophyllaceae). *American Journal of Botany*, 92, 1492–1502.
- Gomez, N.N. & Shaw, R.G. (2006). Inbreeding effect on male and female fertility and inheritance of male sterility in *Nemophila menziesii* (Hydrophyllaceae). *American Journal of Botany*, 93, 739–746.
- Gotoh, A., Ito, F. & Billen, J. (2013). Vestigial spermatheca morphology in honeybee workers, *Apis cerana* and *A. mellifera* from Japan. *Apidologie*, 44, 133–143.
- Grant, J.B. (2006). Diversification of gut morphology in caterpillars is associated with defensive behavior. *Journal of Experimental Biology*, 209, 3018–3024.
- Hartstone-Rose, A., Long, R.C., Farrell, A.B. & Shaw, C.A. (2012). The clavicles of *Smilodon fatalis* and *Panthera atrox* (Mammalia: Felidae) from Rancho La Brea, Los Angeles, California. *Journal of Morphology*, 273, 981–991.
- Kardong, K.V. (2008). *An Introduction to Biological Evolution*, 2nd Ed. Boston, MA: McGraw-Hill.
- Kardong, K.V. (2011). *Vertebrates: Comparative Anatomy, Function, Evolution*. Boston, MA: McGraw-Hill.
- Kearney, M. (2002). Appendicular skeleton in amphisbaenians (Reptilia: Squamata). *Copeia*, 2002, 719–738.
- Kearney, M., Anderson Maisano, J. & Rowe, T. (2005). Cranial anatomy of the extinct amphisbaenian *Rhineura hatcherii* (Squamata, Amphisbaenia) based on high-resolution computed x-ray tomography. *Journal of Morphology*, 264, 1–33.
- Kerney, R.R., Blackburn, D.C., Müller, H. & Hanken, J. (2012). Do larval traits re-evolve? Evidence from the embryogenesis of a direct-developing salamander, *Plethodon cinereus*. *Evolution*, 66, 252–262.
- Koop, C.E. & Schaeffer, F.A. (1987). *Whatever Happened to the Human Race?* Wheaton, IL: Crossway.
- Liman, E.R. & Innan, H. (2003). Relaxed selective pressure on an essential component of pheromone transduction in primate evolution. *Proceedings of the National Academy of Sciences USA*, 100, 3328–3332.
- Longo, S., Riccio, M. & McCune, A.R. (2013). Homology of lungs and gas bladders: insights from arterial vasculature. *Journal of Morphology*, 274, 687–703.
- Maxwell, E.E. & Larsson, H.C.E. (2007). Osteology and myology of the wing of the emu (*Dromaius novaehollandiae*), and its bearing on the evolution of vestigial structures. *Journal of Morphology*, 268, 423–441.
- McGowen, M.R., Clark, C. & Gatesy, J. (2008). The vestigial olfactory receptor subgenome of odontocete whales: phylogenetic congruence between gene-tree reconciliation and supermatrix methods. *Systematic Biology*, 57, 574–590.
- Mehta, R.S. & Wainwright, P.C. (2007). Biting releases constraints on moray eel feeding kinematics. *Journal of Experimental Biology*, 210, 495–504.
- Menton, D.N. (2010). Vestigial organs – evidence for evolution? In K. Ham (Ed.), *The New Answers Book 3* (pp. 229–240). Green Forest, Arkansas: Master Books.
- Miura, T. (2005). Developmental regulation of caste-specific characters in social-insect polyphenism. *Evolution and Development*, 7, 122–129.
- Moch, J.G. & Senter, P. (2011). Vestigial structures in the appendicular skeletons of eight African skink species (Squamata, Scincidae). *Journal of Zoology*, 285, 274–280.
- Morris, H.M. (1974). *Scientific Creationism*. El Cajon, CA: Master Books.
- Müller, H., Oommen, O.V. & Bartsch, P. (2005). Skeletal development of the direct-developing caecilian *Gegeneophis ramaswamii*. *Zoomorphology*, 124, 171–188.
- Napoleão, P., Sousa Reis, C., Alves, L.C. & Pinheiro, T. (2005). Morphologic characterization and elemental distribution of *Octopus vulgaris* Cuvier, 1797 vestigial shell. *Nuclear Instruments and Methods in Physics Research B*, 231, 345–349.
- Nweeia, M.T., Eichmiller, F.C., Hauschka, P.V., Tyler, E., Mead, J.G., Potter, C.W. & others (2012). Vestigial tooth anatomy and tusk nomenclature for *Monodon monoceros*. *Anatomical Record*, 295, 1006–1016.
- Ortega-Chávez, N. & Stauffer, F.W. (2011). Ontogeny and structure of the acervulate partial inflorescence in *Hyophorbe lagenicaulis* (Arecaceae: Arecoideae). *Annals of Botany*, 108, 1517–1527.
- Ostrovsky, A.N., Grischenko, A.V., Taylor, P.D., Bock, P. & Mawatari, S.F. (2006). Comparative anatomical study of internal brooding in three anascan bryozoans (Cheilostomata) and its taxonomic and evolutionary implications. *Journal of Morphology*, 267, 739–749.
- Peterková, R., Lesot, H. & Peterka, M. (2006). Phylogenetic memory of developing mammalian dentition. *Journal of Experimental Biology*, 306B, 234–250.
- Peterková, R., Peterka, M., Viriot, L. & Lesot, H. (2002). Development of the vestigial tooth primordial as part of mouse odontogenesis. *Connective Tissue Research*, 43, 120–128.
- Prince, J.S. & Johnson, P.M. (2006). Ultrastructural comparison of *Aplysia* and *Dolabifera* ink glands suggests cellular sites of anti-predator protein production and algal pigment processing. *Journal of Molluscan Studies*, 72, 349–357.
- Reece, J.B., Urry, L.A., Cain, M.L., Wasserman, S.A., Minorsky, P.V. & Jackson, R.B. (2011). *Campbell Biology*, 9th Ed. Boston, MA: Benjamin Cummings.
- Regoes, A., Zourmanou, D., Léon-Avila, G., van der Giezen, M., Tovar, J. & Hehl, A.B. (2005). Protein import, replication, and inheritance of a vestigial mitochondrion. *Journal of Biological Chemistry*, 280, 30557–30563.
- Rehorek, S.J. & Smith, T.D. (2006). The primate Harderian gland: does it really exist? *Annals of Anatomy*, 188, 319–327.
- Ridley, M. (2004). *Evolution*, 3rd Ed. Oxford, UK: Blackwell.
- Rudall, P.J., Bateman, R.M., Fay, M.F. & Eastman, A. (2002). Floral anatomy and systematics of Alliaceae with particular reference to *Gilliesia*, a presumed insect mimic with strongly zygomorphic flowers. *American Journal of Botany*, 89, 1867–1883.
- Scott, G.B.D. (1980). The primate caecum and appendix vermiformis: a comparative study. *Journal of Anatomy*, 131, 549–563.
- Sekiguchi, H., Moriya, M., Nakayama, T. & Inouye, I. (2002). Vestigial chloroplasts in heterotrophic stramenopiles *Pteridomonas danica* and *Ciliophrys infusioinum* (Dictyochophyceae). *Protist*, 153, 157–167.
- Senter, P. (2010). Vestigial skeletal structures in dinosaurs. *Journal of Zoology*, 280, 60–71.
- Simões-Lopes, P. & Gutstein, C.S. (2004). Notes on the anatomy, positioning and homology of the pelvic bones in small cetaceans (Cetacea, Delphinidae, Pontoporidae). *Lajam*, 3, 157–162.
- Starr, C. & Taggart, R. (2004). *Biology The Unity and Diversity of Life*, 10th Ed. Belmont, CA: Thompson Brooks Cole.
- Streltsov, V.A., Varghese, J.N., Carmichael, J.A., Irving, R.A., Hudson, P.J., Nuttall, S.D. & Springer, T.A. (2004). Structural evidence for evolution of shark Ig new antigen receptor variable domain antibodies from a cell-surface receptor. *Proceedings of the National Academy of Sciences USA*, 101, 12444–12449.
- Strittmatter, L.I., Negrón-Ortiz, V. & Hickey, R.J. (2002). Subdioecy in *Consolea spinosissima* (Cactaceae): breeding system and embryological studies. *American Journal of Botany*, 89, 1373–1387.
- Tague, R.G. (2002). Variability of metapodials in primates with rudimentary digits: *Ateles geoffroyi*, *Colobus guereza*, and *Perodicticus potto*. *American Journal of Physical Anthropology*, 117, 195–208.
- Tamatsu, Y., Tsukahara, K., Hotta, M. & Shimada, K. (2007). Vestiges of vibrissal capsular muscles exist in the human upper lip. *Clinical Anatomy*, 20, 628–631.

- Volpe, E.P. & Rosenbaum, P.A. (2000). *Understanding Evolution*, 6th Ed. Boston, MA: McGraw-Hill.
- Walker-Larsen, J. & Harder, L.D. (2001). Vestigial organs as opportunities for functional innovation: the example of the *Penstemon* staminode. *Evolution*, 55, 477–487.
- Yoshizawa, M. & Jeffery, W.R. (2008). Shadow response in the blind cavefish *Astyanax* reveals conservation of a functional pineal eye. *Journal of Experimental Biology*, 211, 292–299.
- Zhang, J. & Webb, D.M. (2003). Evolutionary deterioration of the vomeronasal pheromone transduction pathway in catarrhine primates. *Proceedings of the National Academy of Sciences USA*, 100, 8337–8341.
- Zubidat, A.E., Nelson, R.J. & Haim, A. (2010). Photoentrainment in blind and sighted rodent species: responses to photophase light with different wavelengths. *Journal of Experimental Biology*, 213, 4213–4222.

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