Segmentation, body symmetry and the organization of the central nervous system in echinoderms

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The organization of the echinoderm central nervous system (CNS) is striking because it varies widely from that of other bilaterians; however, the basis for this is unknown. In the present paper, I identify echinoderms as compound and I show that this is the basis for their radial symmetry and the organization of their CNS. The asteroids, as I show, comprise of bilaterally symmetrical zooids arranged radially. Furthermore, I show that segmentation is the mechanism by which the gene *Sonic hedgehog* (*Shh*) bifurcates and duplicates patterning.

Keywords: nervous system organization, bilateral symmetry, radial symmetry, compound animals, echinoderm body plan, cnidarian body plan

Body symmetry and the organization of the CNS varies widely among the various groups of bilaterians. Here I show that variation in the body plan and organization of the CNS in echinoderms can be accounted for by a compound morphology, and that varying extents of segmentation is the mechanism by which *Shh* bifurcates and duplicates patterning.

Results and discussion

Previous research has shown that when a section of tissue at the posterior edge of the chick wing bud, known as the zone of polarizing activity (ZPA), is transplanted in the anterior edge of the wing bud, it results in a mirror-image duplication of the digits, such

22   that the duplicated anteroposterior patterning is of reverse polarity in organization relative

23   to the proximodistal axis[1]. ZPA signalling has been isolated to the Shh morphogen[2]. There

24   is an equivalent *hedgehog* gene in *Drosophila* that, as with *Shh*, was shown to be involved

25   in the duplication and polarity of patterning[3]. Shubin and Alberch[4] suggested that

26   vertebrate limbs originated by a pattern forming process involving bifurcation,

27   segmentation and condensation. The fin bones of flying fish (Exocoetidae) display a

28   morphology consistent with this idea (Fig. 1a). Likewise, the wings of spongeflies

29   (Sisyridae) display the same pattern (Fig. 1b). A hedgehog protein signals the patterning of

30   the wing skeleton of insects as it does in the limb bones of vertebrates[5,6]. A previous study

31   proposed that the limbs do not develop by a branching mechanism[7], yet here it can be

32   seen, in the fins of flying fish, a consistent pattern of bifurcation from proximal to distal

33   skeletal elements. In addition to its role in the patterning of the limb bones[2,8], *Shh* is also

34   involved in the branching of the lung[9]. And it plays a part in the development of the

35   median hinge point (MHP) of the neural plate[8]. During neurulation, the neuroepithelial

36   cells at the MHP become predominantly short, wedge-shaped and line a furrow, while

37   those in the adjacent areas of the neural plate remain mainly long and spindle-shaped[10–12].

38   Prior studies have shown that the MHP does not drive bending of the neural plate, which

39   can still occur in the absence of the MHP, but is instead involved in the development of

40   the normal cross-sectional form of the neural tube in which it consists of thin floor and

41   roof plates, a narrow lumen and thick lateral walls[11,12] (Fig. 2). Furthermore, the MHP

42   segments the neural plate. For example, in addition to the furrow[11,12], *Pax-2*, *Pax-3* and

43   *Pax-6* expression occurs within each of the two lateral walls of the neural tube but not

44   across the floor plate[8]. When there is no MHP, expression of these genes is continuous

45   across the ventral neural tube[8], which is thick like the lateral walls[12]. Additionally, past

46   experiments have replicated pattern duplication via segmentation. For example,

47   Spemann[13,14] showed that when he constricted the eggs of the newt *Triturus vulgaris* with

48   a ligature along the cleavage furrow at the two-cell stage, it later resulted, in some cases,

49   in the development of newts with anterior duplication. The extent of the duplication

50   corresponded with the degree of constriction, and when the eggs were divided completely,

51   it sometimes resulted in twins[13,14]. Such constriction is segmentation of varying degrees.

52   Segmentation is, as such, the underlying role of the MHP, and segmentation is the

53   mechanism by which *Shh* is involved in pattern duplication. *Shh* is involved in

54   segmentation, and segmentation leads to development resulting in pattern duplication.

55   Furthermore, bifurcation is partial segmentation in which only part of the structure is

56   duplicated into a homologous pair, as evident by the aforementioned experiments

57   involving newts. It is a means by which to increase complexity, such as in the lungs and

58   limbs, and it is a different form of segmentation from that which results in metameres.

59   Segmentation is particularly apparent when the segments are diverged, and the

60   aforementioned experiments demonstrate that segmentation is sufficient to lead to pattern

61   duplication.

62   The echinoderms appear unusual in their adult form: most of the asteroids produce

63   bilaterally symmetrical larvae, but the adults are radially symmetrical[15]. Each of a sea stars

64   rays are structurally complex yet virtually identical, which suggests that they are

65   homologous and, therefore, the result of duplication. The blue sea stars (*Linckia laevigata*)

66   typically have five rays and can be radially divided into five virtually identical segments,

67   which suggests that each of these segments is a zooid because they comprise entirely of

68   them, such that when the duplicate segments are removed, that which is left is that which

69   is duplicated in whole. Furthermore, each segment is almost self-contained with a set of

70   organs needed to survive and reproduce that is echoed in each of the other segments, like

71   each zooid in compound ascidians. This morphology can be referred to as *radially*

72   *compound*. Basket stars are radially compound like sea stars, but each of their rays

73   bifurcate multiple times. Like the ophiuroids, the crinoids and echinoids are also radially

74   compound for the same reason as sea stars due to their relatively similar body plan,

75   although sea urchins have the general outer shape of a spiny oblate spheroid. The nervous

76   system of sea stars and the other aforementioned echinoderm groups is distinct: each zooid

77   has a longitudinal nerve cord that forms one of the radial nerves in the complete animal.

78   Hence, the compound morphology is the basis for the organization of the CNS and radial

79   symmetry in these animals. The compound ascidians *Botryllus schlosseri*, for example, are

80   radially symmetrical chordates in which the zooids radiate from a central cloacal siphon,

81   and the nervous system of each zooid is, likewise, radial to the complete animal. The

82   zooids of these radially symmetrical bilaterians, like those of the aforementioned

83   echinoderms, are bilaterally symmetrical but radially arranged. The centre of radially

84   compound animals is the anterior or posterior end of each zooid. Holothurians have an

85   elongated body and, like planarian flatworms, their nerve cords run in parallel (Fig. 3).

86   The nerve cords are not permanently parallel in the radially compound animals, instead

87   they radiate about a central axis. Cnidarians are also radially symmetrical. Moon jellies

88   (*Aurelia aurita*) comprise of virtually identical quarters in the medusa. And as with sea

89   stars, this suggests that these repeating segments are homologous, which further suggests

90   that they are zooids because these animals also comprise entirely of them, such that they

91   too are radially compound. Furthermore, they have gonads in each of the four segments.

92   Sea stars have gonads in each of their rays.

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125   **Ethics approval and consent to participate**
126   Not applicable.

127   **Consent for publication**
128   Not applicable.

129   **Availability of data and materials**
130   Data sharing not applicable to this article as no datasets were generated or analysed during
131   the current study.

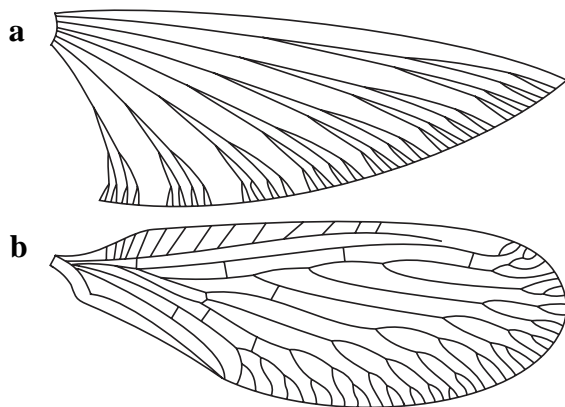132   **Competing interests**
133   I declare that I have no competing financial, professional or personal interests that may
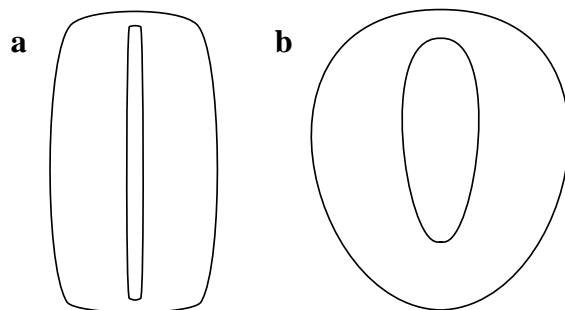134   have influenced the work described in this manuscript.

141

142 **Fig. 1: Bifurcation in the skeletal pattern schematic. a, b,** The branching pattern seen in

143 the fin bones of flying fish (**a**) is analogously also found in the wings of sponge flies (**b**).

144

145 **Fig. 2: Neurulation and the MHP schematic. a,** The characteristic cross-sectional form

146 of the neural tube consists of thin floor and roof plates, a narrow lumen and thick lateral

147 walls[14]. Bending of the neural plate is concentrated at the MHP, which is located at the

148 ventral midline of the neural tube where the cells line a furrow[12–14]. **b,** If there is no MHP,

149 then the ventral neural tube remains thick like the lateral walls, and bending is distributed

150 more evenly[14].
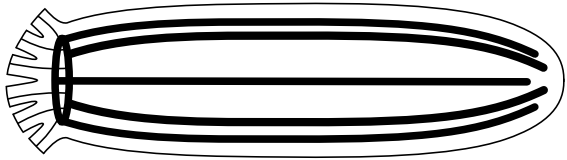
151

152 **Fig. 3: Sea cucumber nervous system schematic.** The longitudinal nerve cords of these

153 animals are parallel with one another like those of planarians. In the sea stars, the radial

154 nerves are not parallel, instead they radiate about a central axis.