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ARTICLE

Somites without a clock

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Abstract

The formation of body segments (somites) in vertebrate embryos is accompanied by molecular oscillations ("segmentation clock"). Interaction of this with a wave travelling along the body axis (the "clock-and-wavefront model") is generally believed to control somite number, size and axial identity. Here we show that a clock-and-wavefront is unnecessary for somite formation. Non-somite mesoderm treated with Noggin generates many somites that form simultaneously, without cyclic expression of Notch-pathway genes, yet have normal size, shape and fate. These somites have axial identity: the Hox-code is fixed independently of somite fate. However they are not subdivided into rostral and caudal halves, necessary for neural segmentation. We propose that somites are self-organizing structures whose size and shape is controlled by local cell-cell interactions.

Main text

The mesoderm of the embryo, from which the cardiovascular and musculo-skeletal systems arise, derives from the primitive streak (PS) during gastrulation. High Bone Morphogenetic Protein (BMP) at the posterior PS generates ventral mesoderm (blood vessels, lateral and extraembryonic mesoderm) whereas lower levels near the anterior tip generate paraxial mesoderm, from which somites (future striated muscle and axial skeleton) develop(*1*). Somites are epithelial spheres that form sequentially from head to tail, on either side of the spinal cord. The combination of a molecular clock (cell-autonomous Notch and Wnt oscillations) and a wave travelling the length of the paraxial mesoderm(*2, 3*) is thought to regulate the number, size, timing of formation and axial identity(*4-6*) of somites. Since the BMP antagonist Noggin is sufficient to transform ventral cells to a dorsal (somite) fate(*7, 8*), we applied Noggin as evenly as possible(*9*) to dorsalize posterior PS explants from quail or GFP-transgenic chick embryos and test whether somites could be generated independently of a "segmentation clock"(*10, 11*). Explants from stage-5(*12*) embryos were incubated in Noggin for 3h, then grafted into a remote (extraembryonic) region of a host chick embryo surrounded by Noggin-soaked beads (Fig. 1 A-B). A few hours later (total 9-12h), 6-14 somite-like structures had formed, arranged as a "bunch-of-grapes" (Fig. 1 C-E) rather than in linear sequence. Like normal somites, they express *paraxis*(*8*) (Fig. 1 F-G) and consist of epithelial cells around a lumen (Fig. 1 G-J), with apical N-cadherin and a Fibronectin-positive basal lamina (Fig. 1 H-J). The size of each is normal: Fig. 1K compares ectopic and normal somite volumes calculated from living embryos and multi-photon cross-sectional areas with and without the lumen (t-tests P=0.496, 0.401 and 0.493 respectively).

To test whether the ectopic somites can give rise to normal somite derivatives, we replaced individual recently-formed somites in 10-14 somite secondary hosts with ectopic GFP-transgenic somites (Fig. 1L). After 2-3 days (stage 19-25) the grafted somite was well integrated (Fig. 1 M) and expressed the sclerotome/vertebral marker *Pax1* (Fig. S1; n=6) and the dermomyotome/muscle marker *MyoD* (Fig. 1 N-P; n=4) in the correct positions. Some blood vessels were also generated (Fig. S1), which may be normal somite derivatives(*13, 14*) or cells retaining their original lateral fate. Thus, the structures in the "bunch-of-grapes" are indeed somites.

To test whether they form sequentially or simultaneously, we filmed ectopic GFP-transgenic somite formation using time-lapse microscopy. About 6-14 somites form in just 2 hours (9-11h after grafting; Movies S1-S2; Fig. S2). Since so many somites can form almost synchronously suggests that the ectopic somites form independently of a clock. To assess the molecular clock, we examined embryos at different time points prior to ectopic somite formation for expression of "clock-genes" *Hairy1* (Fig. 2 A-D), *Hairy2* (Fig. 2 E-H) and *LFng* (Fig. 2 I-L) at 45 min intervals between 3-7.5 hours following exposure of PS explants to Noggin. Although host embryos displayed typical(*10*) strong variations in the pattern of expression, the explants showed only subtle variations, not like a pre-pattern of the somites that would later form. Moreover, when examining many embryos for each marker at a particular time point (Fig. S3), oscillatory expression was evident in the host embryo but the explants (insets) show comparatively uniform expression. Examination of *Dapper1* and *-2* expression suggests that Noggin-treated mesoderm may be able to generate somites without passing through a presomitic-like state (Fig. S4). These results strongly suggest that the ectopic somites form simultaneously and without cyclic expression of "clock-genes".

Each somite is normally subdivided into a rostral and a caudal half, a property subsequently required for segmentation of the peripheral nervous system(*15*). To test whether the ectopic somites are subdivided we examined expression of caudal (*Hairy1*, *Hairy2*, *LFng*, *Uncx4*.1, *Meso2*) and rostral (*EphA4*) markers. None of them revealed subdivision of the ectopic somites. *Hairy1* (0/22), *Meso2* (0/22) and *EphA4* (0/19) were not expressed (Fig. 3 A-C), *LFng* (22/24) (Fig. 3D) and *Hairy2* (8/8) (Fig. 3E) were expressed weakly and uniformly throughout the somites and *Uncx4.1* (13/19) (Fig. 3F) was patchy (Fig. 3F). Therefore ectopic somites seem to lack coherent rostrocaudal identity, since the patterns of different genes are inconsistent to each other. As neural crest cells and motor axons normally only migrate through the rostral half of the sclerotome(*15*), we used this as an additional test of somite patterning. An ectopic GFP-somite was grafted instead of a normal somite in a secondary host (Fig. 1L). At stage 22-25, the patterns of motor axon growth (Fig. 3 G-I) and neural crest migration (Fig. 3 J-O) were disrupted. Abnormalities included an enlarged gap between motor roots (Fig. 3 G-I), or fusion of adjacent ventral roots and dorsal root ganglia (Fig. 3 J-L), or several small ganglia formed within a grafted somite (Fig. 3 M-O), as if the somite contained random islands of permissive (non-caudal) cells, exploited by axons and crest cells. These results suggest that the ectopic somites are not subdivided into rostral and caudal halves, consistent with the proposal(*16*) that the clock is required for this feature of segmentation.

During normal development, the occipital somites (most cranial 4-5 somites) form almost simultaneously rather than in sequence (Movie S3), and lack expression of some rostral/caudal markers(*17-19*). Could the ectopic somites be occipital? We examined expression of Hox genes(*20, 21*) (Fig. 4 A-P): *Hoxb3* (Fig. 4 A,C) and *Hoxb4* (Fig. 4 E,G) were both expressed (Fig. 4 B,D,F,H), suggesting that they are not occipital. *Hoxb6* and *Hoxb9* were not expressed (Fig. 4 F,J) suggesting that they are cervical (somite 8-9). The posterior PS of stage 5 donor

embryos expresses similar genes: *Hoxb3* and *b4* but not *b6* or *b9* (Fig. 4 A, E, I, M); the latter start to be expressed later (stage 7-8; Fig. 4 C, G, K, O). We therefore tested whether somites made from PS from older embryos (stage-8), express these markers. Indeed they do (Fig. 4 L,P). This confirms that the Hox code imparting axial identity to cells is already present in the PS(*22*), independently of the segmentation clock(*6*) and suggests that the axial identity of the ectopic somites is specified according to which Hox genes are expressed in the posterior PS at the time of explantation, even though this region does not normally contribute to somites. Therefore either exit of cells from the PS, or more likely inhibition of BMP by Noggin, arrests the molecular clock controlling expression of Hox genes that impart axial identity(*23*). In vivo, this may happen as presomitic cells leave the BMP-expressing PS and lie next to the notochord, the endogenous source of Noggin.

The clock-and-wavefront model requires both an oscillator and a wave. In zebrafish, changing the period of molecular oscillations affects somite number and size(*5, 6*). We show that somites can form without oscillations of “segmentation clock” genes; all of their properties are normal, except for their rostrocaudal subdivision. Moreover, waves and gradients are also unnecessary, since the spatial organization and simultaneous formation of the ectopic somites does not seem compatible with this. We therefore propose that the main function of the clock is to subdivide somites into rostral and caudal halves, and to couple this to somite formation.

If clock-and-wavefront mechanisms are not required to control somite formation, what does? Our observations implicate local cell-cell interactions. Embryological experiments(*24*) suggest that somites are self-organising structures, regulated by intrinsic properties of the cells and packing constraints for cells undergoing mesenchymal-to-epithelial conversion as they form spheres. We tested this in computer simulations using CompuCell-3D(*25, 26*), with the following assumptions: (1) a cell mass is exposed to Noggin evenly and simultaneously; (2) in response, cells polarize and elongate; (3) polarized cells secrete extracellular-matrix; (4) polarized cells have to be exposed to extracellular space at both their apical and basal surfaces; (5) tight junctions form at the apical ends; (6) misplaced cells rearrange their polarity and attach to their appropriate ends(*27*). This causes cells to become arranged in spherical masses around a lumen (Movie S4)(*9*). After a transition period of intense cell rearrangement, the somites stabilize. The number of cells they contain is relatively invariant and their structure is similar to that seen in vivo. There is no tendency to merge into a giant structure, nor do very small stable somites form. We propose that somite size and shape can be controlled entirely by local cell interactions, such as adhesion and packing constraints of cells transitioning between mesenchyme and a polarized epithelium(*28*). Inhibition of BMP by Noggin may be a trigger for this conversion, consistent with the abnormal somite formation in Noggin-null mice(*29*) and may also “freeze” molecular determinants of axial identity (Hox-code). In normal embryos, the “segmentation clock” and associated wave are likely to play a role in regulating the timing of somite formation and coupling this to the subdivision of each somite into rostral and caudal sub-compartments.

Figure legends

Figure 1. **BMP inhibition generates normal somites. A-E**. Experimental design. The PS of a donor quail or GFP-transgenic embryo is excised, exposed to Noggin and grafted surrounded by Noggin-beads to the periphery of a host chick embryo (A, B; arrow). After overnight incubation, a "bunch of grapes" of somite-like structures appear (C,D) which fluoresce if the donor is a GFP-transgenic embryo (E). **F-Q.** The ectopic structures are real somites: they express *paraxis* (F, G) and N-cadherin (green in H-J) and are surrounded by a Fibronectin matrix (red in H-J). Multi-photon confocal sections through normal (I) and ectopic (J) somites were used to estimate somite sizes (K). When an ectopic somite is grafted instead of a somite in an older embryo (L), the graft incorporates well (M). After 2-3 days, the grafted somite appropriately expresses *MyoD* (N-P).

Figure 2. Ectopic somites form without cyclic expression of "segmentation clock" genes. Embryos were fixed at 45 min intervals (examples shown at 3, 5.15, 6.45 and 7.5h after grafting to a host embryo) and stained for expression of *Hairy1* (A-D), *Hairy2* (E-H) and *LFng* (I-L). The in situs were developed to reveal the "segmentation clock" in pre-somitic cells of the host. Although patterns of expression in the presomitic mesoderm of the host are dynamic, no significant differences in expression are seen in the graft (insets).

Figure 3. Ectopic somites are not subdivided into rostral and caudal halves. A-F. Ectopic somites were analysed for expression of caudal (*Hairy1, Meso2*, *LFng, Hairy2* and *Uncx4.1*) and rostral (*EphA4*) markers. *Hairy1* (A), *Meso2* (B) and *EphA4* (C) are not expressed, *LFng* and *Hairy2* (D, E) are weak and uniform and *Uncx4.1* is expressed as random patches (F). **G-O**. As a further test of rostrocaudal patterning, embryos grafted as in Fig. 1L were stained for motor axons (neurofilament-associated protein NAP, G-I, brown) or neural crest (HNK1, J-O, brown) and anti-GFP (green in I, L, O). A large gap (G-I), fused roots (J-L) or multiple small ganglia (M-O) form in the ectopic somite (arrows, asterisks). Sections I and L are coronal, O is transverse at the level of the graft.

Figure 4. Ectopic somites have trunk identity, fixed according to the Hox genes expressed in the donor primitive streak. A-P. At stage 5, the posterior PS expresses Hoxb3 (A) and b4 (E) but not b6 (I) or b9 (M). Ectopic somites made from posterior streak explants from these stages show a similar pattern of expression (B, F, J, N). At stage 7-8, the posterior streak expresses all 4 genes (C, G, K, O) as do the ectopic somites formed from it (D, H, L, P).

References

1. I. Muñoz-Sanjuán, A. H. Brivanlou, in *Gastrulation: from cells to embryo.,* C. D. Stern, Ed. (Cold Spring Harbor Press, New York, 2004), pp. 475-489.
2. J. Dubrulle, M. J. McGrew, O. Pourquie, FGF signaling controls somite boundary position and regulates segmentation clock control of spatiotemporal Hox gene activation. *Cell* **106**, 219 (2001).
3. J. Dubrulle, O. Pourquie, fgf8 mRNA decay establishes a gradient that couples axial elongation to patterning in the vertebrate embryo. *Nature* **427**, 419 (2004).
4. J. Cooke, E. C. Zeeman, A clock and wavefront model for control of the number of repeated structures during animal morphogenesis. *Journal of theoretical biology* **58**, 455 (1976).
5. Y. Harima, Y. Takashima, Y. Ueda, T. Ohtsuka, R. Kageyama, Accelerating the tempo of the segmentation clock by reducing the number of introns in the Hes7 gene. *Cell Rep* **3**, 1 (2013).
6. C. Schroter, A. C. Oates, Segment number and axial identity in a segmentation clock period mutant. *Curr Biol* **20**, 1254 (2010).
7. A. Tonegawa, N. Funayama, N. Ueno, Y. Takahashi, Mesodermal subdivision along the mediolateral axis in chicken controlled by different concentrations of BMP-4. *Development* **124**, 1975 (1997).
8. A. Streit, C. D. Stern, Mesoderm patterning and somite formation during node regression: differential effects of chordin and noggin. *Mech Dev* **85**, 85 (1999).
9. Online-Supplementary-Material.
10. I. Palmeirim, D. Henrique, D. Ish-Horowicz, O. Pourquie, Avian hairy gene expression identifies a molecular clock linked to vertebrate segmentation and somitogenesis. *Cell* **91**, 639 (1997).
11. A. C. Oates, L. G. Morelli, S. Ares, Patterning embryos with oscillations: structure, function and dynamics of the vertebrate segmentation clock. *Development* **139**, 625 (2012).
12. V. Hamburger, H. L. Hamilton, A series of normal stages in the development of the chick embryo. *J Morphol* **88**, 49 (1951).
13. R. S. Beddington, P. Martin, An in situ transgenic enzyme marker to monitor migration of cells in the mid-gestation mouse embryo. Somite contribution to the early forelimb bud. *Mol Biol Med* **6**, 263 (1989).
14. C. D. Stern, S. E. Fraser, R. J. Keynes, D. R. Primmett, A cell lineage analysis of segmentation in the chick embryo. *Development* **104 Suppl**, 231 (1988).
15. R. J. Keynes, C. D. Stern, Segmentation in the vertebrate nervous system. *Nature* **310**, 786 (1984).
16. Y. Takahashi, T. Inoue, A. Gossler, Y. Saga, Feedback loops comprising Dll1, Dll3 and Mesp2, and differential involvement of Psen1 are essential for rostrocaudal patterning of somites. *Development* **130**, 4259 (2003).
17. C. Jouve, T. Iimura, O. Pourquie, Onset of the segmentation clock in the chick embryo: evidence for oscillations in the somite precursors in the primitive streak. *Development* **129**, 1107 (2002).
18. T. M. Lim, E. R. Lunn, R. J. Keynes, C. D. Stern, The differing effects of occipital and trunk somites on neural development in the chick embryo. *Development* **100**, 525 (1987).
19. S. Rodrigues, J. Santos, I. Palmeirim, Molecular characterization of the rostral-most somites in early somitic stages of the chick embryo. *Gene Expr Patterns* **6**, 673 (2006).
20. A. C. Burke, C. E. Nelson, B. A. Morgan, C. Tabin, Hox genes and the evolution of vertebrate axial morphology. *Development* **121**, 333 (1995).
21. S. J. Gaunt, Conservation in the Hox code during morphological evolution. *Int J Dev Biol* **38**, 549 (1994).

22. T. Iimura, O. Pourquie, Collinear activation of Hoxb genes during gastrulation is linked to mesoderm cell ingression. *Nature* **442**, 568 (2006).
23. S. A. Wacker, C. L. McNulty, A. J. Durston, The initiation of Hox gene expression in Xenopus laevis is controlled by Brachyury and BMP-4. *Dev Biol* **266**, 123 (2004).
24. C. D. Stern, R. Bellairs, The roles of node regression and elongation of the area pellucida in the formation of somites in avian embryos. *J Embryol Exp Morphol* **81**, 75 (1984).
25. S. D. Hester, J. M. Belmonte, J. S. Gens, S. G. Clendenon, J. A. Glazier, A multi-cell, multi-scale model of vertebrate segmentation and somite formation. *PLoS Comput Biol* **7**, e1002155 (2011).
26. M. H. Swat *et al.*, Multi-scale modeling of tissues using CompuCell3D. *Methods Cell Biol* **110**, 325 (2012).
27. G. G. Martins *et al.*, Dynamic 3D cell rearrangements guided by a fibronectin matrix underlie somitogenesis. *PLoS One* **4**, e7429 (2009).
28. Y. Nakaya, S. Kuroda, Y. T. Katagiri, K. Kaibuchi, Y. Takahashi, Mesenchymal-epithelial transition during somitic segmentation is regulated by differential roles of Cdc42 and Rac1. *Dev Cell* **7**, 425 (2004).
29. J. A. McMahon *et al.*, Noggin-mediated antagonism of BMP signaling is required for growth and patterning of the neural tube and somite. *Genes Dev* **12**, 1438 (1998).

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