**Xenopus Neural Crest Cell Migration in an Applied Electrical Field**

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**ABSTRACT**

*Xenopus* neural crest cells migrated toward the cathode in an applied electrical field of 10 mV/mm or greater. This behavior was observed in relatively isolated cells, as well as in groups of neural crest cells; however, the velocity of directed migration usually declined when a cell made close contact with other cells. Melanocytes with a full complement of evenly distributed melanosomes did not migrate of their own accord, but could be distorted and pulled by unpigmented neural crest cells. Incompletely differentiated melanocytes and melanocytes with aggregated melanosomes displayed the same behavior as undifferentiated neural crest cells, that is, migration toward the cathode. An electrical field of 10 mV/mm corresponded to a voltage drop of <1 mV across the diameter of each cell; the outer epithelium of *Xenopus* embryos drives an endogenous transembryonic current that may produce voltage gradients of nearly this magnitude within high-resistance regions of the embryo. We, therefore, propose that electrical current produced by the skin battery present in these embryos may act as a vector to guide neural crest migration.

Neural crest cells, a population of embryonic migratory cells associated with the dorsal aspect of the neural tube, are precursors of a remarkable number of different tissue types. Neural crest derivatives include the autonomic ganglia, Schwann cells, melanocytes, chromaffin cells, ciliary muscles, facial cartilage, and all of the neurons of the dorsal root ganglia, to name just a few. Despite intensive investigation, the factors involved in dispersal to these different sites remain largely unknown (1-3).

Previous hypotheses of neural crest migration include (a) a gradient of hyaluronic acid or other glycosaminoglycan that could be sensed by the neural crest cells (4), (b) contact guidance due to oriented extracellular matrix fibrils found along the neural tube, notochord, and somites (5), or (c) contact inhibition of cells and persistence of motion, resulting in a net migration of cells toward regions of low population. To these, we would add electrical guidance of neural crest cells, due to a current generated by the skin battery of the embryo (6). This current apparently flows from the skin, through the internal tissues, to the archenteron, and then out of the blastopore (K. Robinson and R. Stump, unpublished observations); current flow via resistive internal tissues will produce an electrical field. This proposition does not conflict with the previous hypotheses and, in fact, is likely to be acting in concert with one or more of them. We base this idea upon the finding that neural crest migration could be guided by electrical fields, as detailed below. A preliminary report of this work has appeared in abstract form (7); similar findings have recently been reported in abstract form by two other groups of investigators (8, 9).

Until recently, there had been no convincing evidence that cells from metazoans migrate directionally in an applied electrical field. This work provides clear-cut evidence for a galvanotactic response, at low electrical field strengths, for such cells. One other well documented example of a galvanotactic response with respect to animal cells is that of Nucitelli and Erickson (10), who find that quail somitic fibroblasts migrate toward the cathode in an applied electrical field. There are claims that peritoneal macrophages migrate directionally toward the anode in an electrical field (11); however, these authors present evidence only for orientation, but not migration, in a field.

**MATERIALS AND METHODS**

*Cell Cultures:* Early experiments were done using Ca ++ - and Mg ++ -free Steinberg's medium and/or collagenase (1 mg/ml in Steinberg's solution; 58 mM NaCl, 0.67 mM KCl, 0.44 mM Ca(NO3)2, 1.3 mM MgSO4, 4.6 mM Tris, pH 7.8-8.0) to dissociate tissue from the anterior 1/6 or dorsal 1/4 of *Xenopus* neurulae. These cells were plated onto acid-cleaned, D- or L-polylysine-treated coverslips in a complete medium (20% L15, 5% fetal calf serum, 2% Penicillin/Streptomycin [10,000 units/ml in Steinberg's solution, pH 7.4-8.0; pH 7.6 gives the best results (12)]. A few experiments used 45°C heat-inactivated fetal calf serum. Later experiments used Ca ++ - and Mg ++ -free or collagenase
dissection to obtain the neural tubes of stage 17–26 embryos (13). These neural tubes then were plated onto 0- or L-polylysine treated, no. 1 glass coverslips, 18 mm square, in complete medium (14). Cells were cultured for 1 to 5 d prior to an electrical field experiment.

This technique took advantage of the normal migratory properties of neural crest cells. In <24 h, many such cells migrated from the neural tube, forming a halo of cells around it. Shortly thereafter, small groups of melanocytes could be observed, interspersed amongst the other angular, unpigmented, neural crest cells. The majority of these unpigmented cells became melanocytes, if allowed to remain in culture for ~5 d.

**Electrical Field Experiments:** Field experiments were done in a specially designed chamber, such that current could be passed via two Ag/AgCl electrodes (in Steinberg’s solution or 58 mM NaCl), each of which was attached to a 10-cm bridge containing gelled 1% Agar or agarose in Steinberg’s solution. The agar bridges provided a barrier for Ag generated by the electrodes, and were of sufficient length to prevent Ag contamination for ~28 h. Prior to an electrical field experiment, the neural tube was removed mechanically, leaving emigrant neural crest cells still attached to the 18-mm glass coverslip. The coverslip containing these cells was inverted into a trough (constructed of no. 1 coverslip material using silicone sealer), measuring 1 x 6 cm. The center of the exterior surface of this coverslip was cleaned first with distilled water, then with ethanol, followed by one drop of mineral oil to improve the optics. Room temperature agar then was used to electrically connect the edges of the 18-mm coverslip to each of the bridges. A cover to prevent evaporation was applied, and the entire chamber was mounted on the stage of an Olympus inverted microscope equipped with Hoffman modulation optics (Olympus Co., New Hyde Park, NY).

Cell migration was followed by either time-lapse photography (Kodak Technical Pan Film 2415) at 0.5-h intervals, or time-lapse videotape (Sony model TVO-9000, MTI-65 camera, and Tektronics 634 high resolution monitor), at a time compression of 96:1. Videotaped records allowed continuous monitoring of the cells, though the resolution of each cell image was much less than that of photographic records. Photographic records did not always allow a clear identification of individual cells after collision, and required a considerable amount of darkroom time.

In a typical experiment, an electrical field of 10–350 mV/mm was applied for 3–5 h followed by 180° reversal of the field for an equal period of time. In some experiments, the cells were observed for 1 h or more, prior to application of the field. The electrode to electrode voltage and the applied current were continuously monitored throughout each experiment; at the end of each experiment, the electrical field strength across the culture was measured directly, using a voltmeter and two Ag/AgCl electrodes. All experiments were performed at room temperature.

**RESULTS**

**Delayed Initial Migration Response**

Both videotaped and photographed time-lapse records revealed that the migration response of cells to the field took some time. (A videotape of four field experiments is available [total real time of 29 h]; 15). Some cells migrated randomly with respect to the electrical field vector for as long as 2 h, prior to recognizing the field vector, and following the vector to the cathode. After a cell responded to the field, however, it could adapt rapidly to changes in the direction of the electrical field; upon reversal of the field, cessation of motion towards the previous cathode often could be detected in <1,000 s, followed by immediate migration to the new cathode.

**Protrusive Activity and Cell Elongation**

An increase in cell protrusive activity frequently was apparent in videotaped records, shortly after the field was applied. Following this, some, but not all, cells elongated such that their longest axis was perpendicular to the field. This perpendicular elongation was transient for many of the cells, as numerous shape changes were observed as these cells moved toward the negative electrode; these cells often assumed multangular shapes without an obvious geometric relationship with respect to the field vector. Other cells, however, did migrate toward the cathode, while retaining an elongated form, which was perpendicular to the field. At present, we regard this ability to move in a direction that is perpendicular to the cell’s longest axis as normal on the substratum used, since identical behavior can be observed in cultures that have not been exposed to an electrical field. In these control cultures, cells that travel perpendicular to their longest axis are often pioneer cells, suggesting that this geometry may favor rapid translocation, or may allow pioneer cells to exert traction on other, slower moving, neural crest cells.

**Unpigmented Neural Crest Cells**

A typical time lapse experiment involving a single unpigmented neural crest cell is shown in Fig. 1. Notice that it took some time for this cell to respond to the field vector, as the tracings are quite close together during the early part of the record. However, upon reversal of the field, a retreat toward the new cathode can be detected within 0.5 h. In reversal experiments with single cells or small groups of cells, we found a migration rate of 17 ± 17 #m/h toward the cathode before reversal; and a migration rate of 24 ± 15 #m/h toward the new cathode after field reversal (unpigmented cells only, n = 14; E = 180–270 mV/mm).

A field reversal experiment involving >100 cells is displayed in Fig. 2. In this experiment, the entire culture was photographed as a single darkfield negative, and as a montage of a part of the culture, at times 0, 4, and 8 h. Between 0 and 4 h, and 4 and 8 h, a fraction of the optical field was photographed at high magnification at 0.5 h intervals. Darkfield negatives (actually positives) were registered using subcellular debris, which does not move. It is clear that during the first 4 h of the experiment, many cells have shifted by 100 #m or more toward the cathode. After reversal, the cells again migrated toward the (new) cathode. A Xenopus embryo is only ~1,000 #m in cross-sectional diameter, so this distance represents roughly 1/10 of the embryo’s complete diameter. Further, a neural crest cell whose ultimate location is in a dorsal root ganglion, for instance, must travel only ~100 #m to reach this position.

An estimate of the likelihood of obtaining the data in Fig. 2 by chance can be made by assuming that the data obey a binomial distribution. In this instance, migration toward the anode and the cathode each has a probability of 0.5, assuming random migration. Cells that failed to move much are discarded. Using only the portion of the optical field that was photographed as a high magnification montage, we note that at least 10 cells migrated toward the cathode during t = 0–4 h (Fig. 2, C and D), and that these cells then migrated back toward the new cathode during t = 4–8 h (Fig. 2, D and E), while none traveled toward the anode; several did not move. The probability of this occurring by chance during random migration is (0.5)10, or ~1: 1 x 10^-4. This is a conservative estimate, since >100 cells must move to generate the images shown in the overlays (Fig. 2, A and B).

**Melanocytes**

Melanocytes were frequently found in our cultures. Mature melanocytes with a complete complement of uniformly distributed melanosomes did not move in a field. However, the processes of these cells did rearrange, often producing a cell with its long axis perpendicular to the field vector, but sometimes also bearing large processes parallel to the vector, as
FIGURE 1 Record of a neural crest cell from the anterior 1/6 of a stage 22 ± 1 embryo, after 1 d in culture. This image was constructed from time lapse photographs taken at 0.5-h intervals. Cells which displayed detectable movement over the course of the record are shaded; subcellular debris, and cells that did not move are white. Electrical field (E vector) strength was 200 mV/mm. The field was on for 1 h prior to this record. (A) Subject (finely stippled, field center) moved toward the cathode (to the left), capturing a neuron (diagonally lined) en passant. Three other cells were displaced somewhat, but showed little net translation. (B) After 5.5 h of the initial field direction, the current was reversed for 5.5 h. The neural crest cell reversed within the first 0.5 h, and migrated towards the new cathode. Near the end of the record, a second cell (coarsely stippled, upper right), also was picked up and carried towards the negative electrode.

well. These melanocytes were frequently moved and distorted considerably by attached unpigmented neural crest cells responding to the field (Fig. 2D). Melanocytes with a submaximal number of melanosomes, and amoeboid melanocytes with aggregated melanosomes, behaved like unpigmented neural crest cells; they traveled toward the cathode, as shown in Fig. 3. For pigmented melanocytes, with a less than maximal number of melanosomes, a migration rate of 11 ± 22 μm/h toward the negative electrode was found before reversal. After reversal, the cells migrated to the new cathode at 32 ± 30 μm/h (n = 24; E = 170 mV/mm, 45° fetal calf serum).

Cell Velocity Parallel to the Field Vector

In previous sections, we have presented cell velocity data that were averaged over a period of 3–5 h, prior to and after
FIGURE 2  Record of neural crest cells obtained from an explanted neural tube (stage 20–21 embryo). The neural tube was cultured for 2 d prior to its removal from the coverslip. An electrical field of 210 mV/mm was applied during 0–4 h, then the field was reversed during 4–8 h. At times 0, 4, and 8 h a darkfield photograph of the entire culture was taken. These negatives were registered using background debris, which does not move, and graphically superimposed. In Fig. 2A, the time zero (white) and 4-h (black) images are shown. It is clear that the cells have migrated toward the cathode (to the left). Likewise, in Fig. 2B, the 4-h (black) and 8-h (white) images are overlayed. During this time the field was reversed; the net movement of cells toward the new cathode is evident. A Venn diagram is present in the upper left of each of Fig. 2, A and B, allowing interpretation of regions of overlap (stippled). A montage of a portion of the neural crest culture on the coverslip at time 0 is shown in 2C. The resulting arrangement of cells at 4 h is shown in 2D, that at 8 h in 2E. Numerous cells that migrated toward the cathode (left) during 0–4 h, again, migrated to the (new) cathode (right), during 4–8 h. Arrows point to identical cells in Figs. 2, A–F, to aid the reader in pattern recognition.

Table I shows some sample velocity data obtained from videotaped records, in which randomly selected, individual cells could be reliably followed. In each of these experiments, field reversal. Here we will show velocity data averaged over one-h intervals, to demonstrate temporal velocity variations within these cultures.
FIGURE 3 Melanocyte migration in an electrical field of 9.4 mV/mm. This figure illustrates the directed migration of incompletely differentiated melanocytes, and melanocytes with aggregated melanosomes; no completely differentiated melanocytes are shown in this culture. The field was applied in each direction for 4 h; photographs are at 1-h intervals, time appears in the lower right corner of each photograph. Cells A and C do not move much, cells D–G respond to the field, cell B divides between 3 and 4 h. Notice that prior to division, cell B is stationary, but that after division, both daughter cells seek the cathode; this is a common feature of mitosing cells. Solid arrows point toward the cathode; the field was reversed ~1 min after the t = 4-h photograph was taken (photographs were taken at 0.5-h intervals and included a larger portion of the culture than is shown, allowing positive identification of labeled cells).

an average increase in velocity toward the cathode was noticed within the first hour of exposure to the field; upon field reversal, the reversal of cell migration was evident within the first hour. Also, these data reveal that the migration of these populations was not constant; considerable variations occurred from one hour to the next. This variation also was apparent when individual cells were considered; the migration of the majority of the cells was distinctly saltatory. Individual cells can maintain a velocity of up to 130 μm/h, parallel to the field vector, averaged over a one-h period. Clearly, this rate of migration is substantial relative to the cross-sectional diameter of the embryo. The third experiment in Table I illustrates the effect of removing the electrical field. A decline in velocity, which persisted for several hours, could be detected within an hour of removing the field; the cells seemed to quickly forget the field direction.

Migration at Low Field Strengths

Neural crest cells, incompletely differentiated melanocytes, and melanocytes with aggregated melanosomes migrated toward the cathode in electrical fields as low as ~10 mV/mm. However, a response by our criterion of reversal of migration upon field reversal was not always observed in these low fields. The major problem here was that undifferentiated neural crest cells appeared to have difficulty separating themselves from mature melanocytes, once close contact was established. Therefore, undifferentiated cells that had followed the field vector during the first half of the experiment but had come into contact with a mature melanocyte during their journey, failed to separate from these stationary melanocytes upon field reversal. To avoid this problem, we chose young, sparsely populated cultures, with no fully differentiated melanocytes, for these experiments. Using these selected cultures, we readily obtained a galvanotactic response at 9 mV/mm as demonstrated in Fig. 3. In this experiment, cells D–G respond to the electrical field by migration toward the cathode. Cells A and C show little migration. Cell B does not move substantially until after mitosis, then both daughter cells seek the
cathode. In the culture used for this figure, 49 cells moved toward the cathode, 13 cells moved toward the anode (t = 0–8 h, data not shown); the odds of this occurring by chance during random migration are roughly 1.5 × 10^2. Two other cultures, in which a field strength of 22 mV/mm was used, gave results that were even more striking. More than 90% of the cells in these cultures migrated toward the cathode, and reversed direction upon field reversal.

**DISCUSSION**

We observed that neural crest cells migrated toward the cathode in an applied electrical field. Some cells migrated randomly for several hours prior to following the electrical field vector toward the cathode; however, once these cells responded to the field, they could rapidly adapt to changes in field direction. The reason for this initial time lag is not presently understood; it may reflect the time needed for synthesis of a crucial protein. These findings are derived from experiments done on a total of several thousand cells, at field strengths as low as 10 mV/mm. An average neural crest cell is roughly 70 μm in diameter, and therefore a voltage drop of ~0.7 mV per cell is produced across each cell, at the lowest field strength. When the electrical field is turned off, the average velocity parallel to the direction of the previous field vector rapidly declines; cells apparently do not remember the direction of the field.

**Field Reversal**

Reversal of the field is an important element in these measurements; without it, one cannot be certain that the cells are not following some other external cue. For example, to have the magnification and resolution necessary to study individual cells, frequently only a portion of the population is observed. While the population as a whole exhibited random migration in the absence of an electrical field, subsets of this population frequently did not. Since these cells migrated radially away from a piece of neural tube, the net migration of the cells is zero. However, if only a fraction of this halo of cells is considered, this subpopulation’s migration is not random; the net migration is away from the source. Other external cues for directional migration also can be envisioned; for instance, graded strain in the coverslip or an O2 gradient in the chamber might influence migration. Therefore, measurements in which the electrical field is applied only in a single direction, without some type of control, are unconvincing. One such control might be to observe the population for some time prior to applying the electrical field, and then attempting to reverse the natural migration direction. This presents considerable technical difficulties, since the chamber would have to be able to pass current in any direction. Because of this, 180° reversal of the electrical field vector would seem to be the most reasonable method.

**Mechanism**

The mechanism used by these cells to sense the field is unknown. This phenomenon clearly is not simple electrophoresis of the cell; since the cell surface is negatively charged, cells would be electrophoresed toward the anode, not the cathode. Electroosmosis, a movement of H2O bound to mobile cations in the electrical double layer near the cell surface, could conceivably push the cells toward the negative electrode, due to the hydrodynamic drag created by this H2O flux. However, cellular debris and subcellular organelles should have roughly the same zeta potential as the cell surface and, therefore, should be subjected to about the same electroosmotic forces as whole cells; this debris does not move except when dislodged by surface tension forces during the assembly of the chambers, or when moved directly by cellular processes.

The fact that large numbers of debris particles formed constellations that were unaltered by the electrical field and by field reversal (see Figs. 2, A and B, and 3) makes it unlikely that an electroosmotic force on the cell as a whole produces the directed migration that we observe.

Electrophoresis and electroosmosis may play a different role, however. These electrokinetic effects can act directly on cell receptors rather than on the whole cell, resulting in a redistribution of receptors within the plane of the membrane (16, 17). For example, if the receptors for fibronectin, a molecule that is chemotactic or haptotactic for neural crest cells (18), were redistributed by the electrical field, then a directional migration response would occur even in the absence of a fibronectin gradient. A gradient of fibronectin itself is unlikely, since the culture medium spans a broad band on either side of the cells; fibronectin which is electrophoresed away from the cells on one side of the culture is replaced by...
fibronectin electrophoresed toward the cells from the opposite side; a fibronectin gradient will not be formed during the time interval used for our experiments.

Electrophoretic redistribution of a chemical used as a signal (similar to cAMP in *Dictyostelium*), which is produced by the neural crest cells themselves, also could result in directional migration. Hyaluronate, or another polysulfated glycosaminoglycan, would be a reasonable candidate for this model, since the high molecular weight and the high (negative) charge of these molecules are conducive to gradient formation in an electrical field. It is known that neural crest cells initiate their migration in an extracellular matrix rich in hyaluronic acid. In early embryos, intercellular spaces are quite narrow (cf. reference 19), and because of this, electrical fields produced by current flowing through an embryo would be relatively large; hyaluronic acid is negatively charged, so the region just beneath the ectoderm would be predicted to contain the highest hyaluronic acid concentrations. This is found to be the case (19).

We have considered the possibility that the delayed initial response of some cells could reflect the time needed either for redistribution of membrane receptors, or for signaling molecules released by the neural crest cells themselves. If a time, $t$, is required for formation of a gradient, then upon reversal of the field a time of $\sim 2t$ is needed to establish an equal gradient in the opposite direction. Therefore, a longer delay time is expected when the field is reversed. This did not occur; neural crest cells responded rapidly to changes in the field direction, apparently ruling out this possibility.

Finally, the electrical field may induce a net ionic flux through these cells, thereby influencing cell migration. In this case, the anodal side of the cell will become slightly hyperpolarized, while the cathodal side is slightly depolarized. This will alter the driving force for ions passing through ionic channels, as well as conceivably opening or closing voltage-gated channels, which are poised near their threshold potential. However, this mechanism is unlikely considering the response to small fields ($<1 \text{ mV per cell diameter}$), and the observed sensitivity of voltage-gated channels in other systems (20).

**Electrically Mediated Migration vs. Migration In Vivo**

The average electrically directed migration rate of $\sim 30 \mu \text{m/h}$ is comparable to the apparent migration rate of 70 $\mu \text{m/h}$ observed in other systems, in vivo (cf. reference 21). The lowest field strength reported here (10 mV/mm) is roughly 50-fold larger than the field strengths expected in vivo, based on measurements performed with a vibrating electrode, on whole embryos (K. Robinson and R. Stump, unpublished results). However, it is important to realize that we are not claiming that 10 mV/mm is required for the threshold response; we are presently attempting to optimize culture conditions, to determine the in vitro field threshold.

If neural crest cells are electrically guided in vivo, they can be expected to migrate along the electrical field vector. The magnitude of the electrical field depends on both the current density and the resistivity. The pathway of the electrical current is not only determined by the skin and the resistivities of internal tissues but also depends on the location of the “leaks” that allow current to flow into the archenteron and then out of the blastopore. It may be that some of the target structures for the neural crest act as current sinks, thereby maximizing current flow toward themselves. This could explain neural crest aggregation to form plexes in the aorta, or colon, for instance. This need not be an active process but could result from something as simple as an absence of tight junctions in some regions.

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**REFERENCES**

1. Le Douarin, N. 1980. Migration and differentiation of neural crest cells. *Curr. Top. Dev. Biol.* 16:31-85.
2. Bronner-Frazer, M. E., and A. M. Cohen. 1980. The neural crest: what can it tell us about cell migration and determination? *Curr. Top. Dev. Biol.* 15:1-25.
3. Le Douarin, N. M., J. Smith, and C. Le Lievre. 1981. From the neural crest to the ganglia of the peripheral nervous system. *Annu. Rev. Physiol.* 43:653-71.
4. Weston, J. A. 1981. The regulation of normal and abnormal neural crest cell development. *Adv. Neurol.* 29:77-95.
5. Lofberg, J., K. Ahlfors, and C. F. Stevens. 1982. Neural crest cell migration in relation to extracellular matrix organization in the embryonic axolotl trunk. *Dev. Biol.* 75:148-167.
6. McCaig, C. D., and K. R. Robinson. 1982. The ontogeny of the transdermal potential difference in frog embryos. *Dev. Biol.* 95:335-339.
7. Stump, R. F., and K. R. Robinson. 1982. Directed movement of Xenopus embryonic cells in an electric field. *J. Cell Biol.* 95(2 Pt. 2):331a. (Abstr.)
8. Erickson, C. A., and Nuccitelli, R. 1982. Embryonic cell motility can be guided by weak electric fields. *J. Cell Biol.* 95(2 Pt. 2):314a. (Abstr.)
9. Cooper, M. S., and R. E. Keller. 1982. Electrical currents induce perpendicular orientation and cathode-directed migration of amphibian neural crest cells in culture. *J. Cell Biol.* 95(2 Pt. 2):332a. (Abstr.)
10. Nuccitelli, R., and C. A. Erickson. 1983. Embryonic cell motility can be guided by physiological-electric fields. *Exp. Cell Res.* In press.
11. Orida, N., and J. D. Feldman. 1982. Directional prostaglandin E1-induced movement of neutrophils in agarose gel. *Cell Motil.* 2:243-255.
12. Hinkle, L. C., C. McCaig, and K. R. Robinson. 1981. The direction of growth of differentiating neurons and myoblasts from frog embryos in an applied electric field. *J. Physiol.* 314:121-135.
13. Nieuwkoop, P. D., and J. Faber. 1956. Normal Table of Xenopus Laevis (Daudin). North-Holland Publishing Co., Amsterdam.
14. Cohen, A. M., and L. R. Konigshofer. 1975. An in vitro approach to the problem of neural crest determination. *Dev. Biol.* 46:262-280.
15. Stump, R. F., and K. R. Robinson. 1982. Directional migration of Xenopus neural crest cells in an applied electric field. Videotape, 26m-50s.
16. Jaffe, L. F. 1977. Electrophoresis along cell membranes. *Nature (Lond.)* 265:600-602.
17. McLaughlin, S., and M.-M. Pop. 1980. The role of electro-osmotic and electrophoretic movement of charged macromolecules on the surfaces of cells. *Biophys. J.* 34:85-93.
18. Greenberg, J. H., S. Seppe, H. Seppe, and A. T. Hewitt. 1981. Role of collagen and laminin in neural crest cell adhesion and migration. *Dev. Biol.* 87:259-266.
19. Derby, M. A. 1978. Analysis of glycocalyxolymic polysaccharides within the extracellular environments encountered by migrating neural crest cells. *Dev. Biol.* 66:323-336.
20. Reuter, H., C. F. Stevens, R. W. Tien, and G. Yellen. 1982. Properties of single calcium channels in cardiac cell culture. *Nature (Lond.)* 297:501-504.
21. Duband, J. J., and P. Thiery. 1982. Distribution of fibronectin in the early phase of avian cephalic neural crest cell migration. *Dev. Biol.* 93:308-323.