ABSTRACT
Growing axons are directed not only by chemical signals but also by electric fields in a process known as galvanotropism. Axons of embryonic neurons extend along the extracellular voltage gradient towards the cathode. During embryonic development neuroepithelial cells function as neural stem cells. The neuroepithelial cell has epithelial type sodium channels (ENaC), and the sodium transport via ENaC of retinal neuroepithelial cells produces extracellular positive direct current (DC) potentials within the retinal neuroepithelium. The amplitude of the positive DC potential is large at the periphery of the embryonic retina, and almost null at the ventral part of the optic cup, where the future optic disc is formed. Retinal ganglion cells are first born at the central part of the optic cup and they extend their axons along the endogenous voltage gradient; the disruption of the DC potential by blocking ENaC results in erroneous path finding of newborn retinal ganglion cell axons. Retinal ganglion cell axons can also be oriented by exogenous electric fields in vitro. Galvanotropism may be used to reform an optic nerve from the retinal ganglion cells that are generated from ES cells and iPS cells.

Keywords
Axon guidance, Galvanotropism, Neuroepithelial cell, Retina.
neuroepithelial cells in the embryonic retina and the role for the electric field in RGC axon orientation.

Neuroepithelial cells produce the extracellular positive DC potential
The neuroepithelial cell has various types of ion channels [7-9], including epithelial type sodium channels (ENaC) [10]. In the course of electrophysiological studies of retinal neuroepithelial cells and newborn RGCs [7], the extracellular potential was recorded from the retinal neuroepithelium in an optic cup isolated from chick embryos [10,11]. Upon penetration of the inner limiting membrane from the vitreous side with a fine glass microelectrode [12], a positive direct current (DC) potential was recorded. Na$^+$ ions enter the neuroepithelial cell through ENaC from the apical side, and are extruded by Na$^+$-K$^+$ pumps in the basal region (Figure 1). The application of a blocker for ENaC (amiloride) reversibly reduces the amplitude of the positive DC potential [10]. Since the extracellular electrical resistance is extremely high due to the tight structure of the epithelium [Supplementary Discussion in 11], and the inner limiting membrane has also high electrical resistance [10], the positive charge is accumulated inside the retinal neuroepithelium. Thus, the sodium transport by neuroepithelial cells generates the extracellular positive DC potential in the basal region of the retinal neuroepithelium.

Endogenous electric fields in embryonic retina
The amplitude of the extracellular positive DC potential is largest at the dorsal part of the optic cup, where the neuroepithelial cells most actively proliferate increasing cell densities [13]. On the other hand, the cells located ventrally in the optic cup are triangular-shaped [1], similar to the wedge-shaped floor plate cell in the neural tube [14]. Since the ventrally located cells have the ion channels that are not responsible for the sodium transport [15], positive potentials are not generated at the ventral part of the developing CNS including the retina. The future optic disc is formed at the ventral part of the optic cup (Figure 2).

The endogenous electric field directs RGC axons towards the future optic disc
RGCs, the first type of retinal neurons, are born at the central part of the optic cup (Figure 2). They extend their axons in the basal region of the retinal neuroepithelium towards the future optic disc. The disruption of the endogenous voltage gradient by applying amiloride to the optic vesicle of chick embryos and to the medium of the organotypic culture of optic cups results in erroneous pathfinding of newborn RGC axons [11]. These results strongly suggest that the endogenous electric field is the guidance cue for orienting RGC axons.

Galvanotropic behavior of RGC axons in constant electric field culture
A culture system was built to apply constant electric fields to retinal strips for quantitative studies of the effect of electric fields on the growth of RGC axons [16]. The orientation of RGC axons growing in vitro mirrors the pattern of axon growth during normal development in vivo [17]. When retinal strips are explanted from the segment that is originally dorsal to the optic nerve head, numerous axons emerge from the ventral side of the retinal strip after 24 hours in vitro (Figures 3A and 3B). It is likely that these ventrally growing axons are already oriented before the explant [17]. On the dorsal side of the retinal strip, outgrowing axons are rarely observed (Figures 3A, and 3B). However, by applying electric fields in the direction opposite to the endogenous field,
many axons extend from the dorsal side (Figure 3C). The reverse, dorsally directed electric field can orient RGC axons at the field strength quite weaker than the endogenous electric field [16]. On the contrary, the ventrally directed field enhances the ventral growth (Figure 3D).

**Molecular mechanisms for electric axon guidance**

McCaig proposed a model for cathodal orientation of growing axons [2]. In this model, membrane receptors, such as nicotinic acetylcholine receptors, accumulate towards the cathode-facing side of growth cones, which leads to cathodal steering of the growth cone through cytoplasmic Ca\(^{2+}\) elevation. However, it remained to be answered whether the asymmetric redistribution of receptors is required for cathodal orientation. The transmembrane potential would be depolarized at the cathode-facing side, and hyperpolarized at the anode-facing side. These changes in the membrane potential may cause asymmetric activation of voltage-dependent Ca\(^{2+}\) channels. However, its contribution to axon steering is controversial [18]. McCaig also proposed that voltage-sensitive phosphatases act as voltage sensors in electric fields [19]. However, these voltage-sensing molecules have a transmembrane voltage-sensing domain, and a significant difference in the transmembrane potential between the anode- and cathode-facing sides is required for asymmetric activation of these voltage-sensitive molecules.

From the fact that weak electric fields can cause galvanotropic behavior [2,16], it seems unlikely that the asymmetric activation of voltage-sensing molecules is responsible for axon steering. McCaig’s group demonstrated roles for the GTPases Rac, Cdc42 and Rho [20], and for microtubules and microfilaments [21] in axon steering by electric fields. However, it remained unknown what is the cell surface molecule that is asymmetrically activated in electric fields. A preliminary study suggested the involvement of integrins in electric axon guidance [22]. Further studies are required to reveal the molecular mechanism for electric axon orientation.

**Future directions**

It is possible to generate an optic cup, layered retinae, and RGCs with functional axons from ES cells and iPS cells [23-25]. However, optic nerves are not formed in these stem cell cultures. The reason for the lack of optic nerves may be that there is no guidance cue for the generated RGC axons. To guide these RGC axons, galvanotropism may be used. By applying electric fields, RGC axons could be gathered to form an optic nerve. Galvanotropism has been already applied to injured spinal cords for axon regeneration [19]. Restoration of vision by transplantation of the generated retina and RGCs from stem cells to degenerated retinae depends on the reformation of optic nerves.

**References**

10. Yamashita M. Epithelial sodium channels (ENaC) produce extracellular positive DC potentials in the retinal