Electroreception

Outline:

Introduction

Detection of weak electric currents

Anatomy of receptor cells

Ampullae

Tuberous organs

Functions of receptor cells

- ***Ampullae***
  - Active
  - Passive

Tuberous organs

Electrocommunication

Electrogenesis

Organ structure

- ***How is electricity generated?***

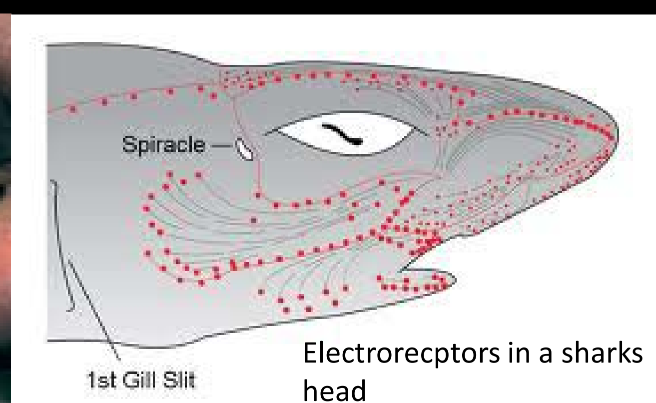
Introduction

Electroreception is the biological ability to perceive electrical impulses

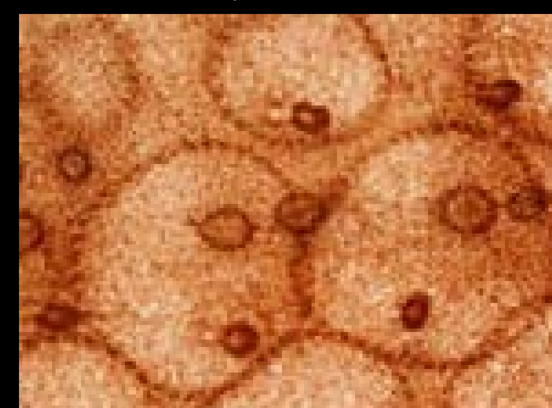
The primary functions of electroreception are OBJECT LOCATION (electrolocation), which is important for feeding and navigation in turbid or dark environments, ORIENTATION, and COMMUNICATION (electrocommunication), which is often species specific.

So, which fish use electroreception?

The skin of a young lungfish showing the single line of mechanoreceptors along the body, with smaller electroreceptors above and below



Electrorecptors in a sharks head



1. DISTRIBUTION OF ELECTRORECEPTION AMONG LIVING FISHES

ALL FISHES

NON-ELECTRORECEPTIVE FISHES: specialized receptors absent; most all teleosts, i.e., the vast majority of fishes

ELECTRORECEPTIVE FISHES: normally use electrical signals present in the environment; specialized receptors present

NON-ELECTRIC FISHES: electric organs absent; **passive electroreception**; sharks, rays, polypterids, eels, catfishes, lungfishes

ELECTRIC FISHES: specialized electric organs present; **active electroreception**; 13 families in six relatively unrelated orders

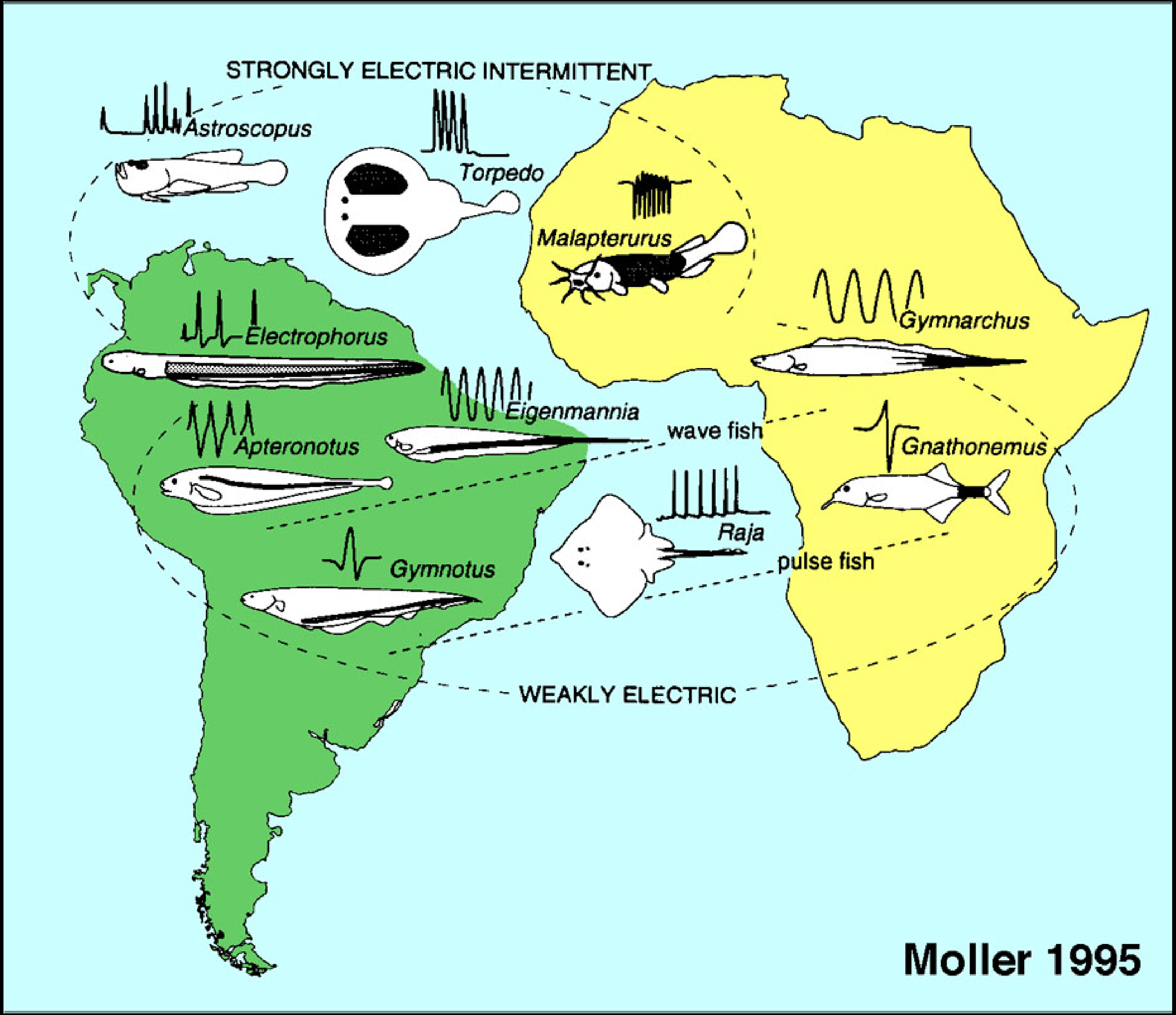
MARINE SPECIES: sharks, rays, the eel genus *Anguilla*, marine catfishes

FRESHWATER SPECIES: catfishes, freshwater rays (*Potamotrygon*), and lungfishes

WAVE SPECIES: electric organ discharge is sinusoidal; usually high frequency, with very small variation; Gymnarchidae and some gymnotids, e.g., *Sternopygus*, *Eigenmannia*, and *Apteronotus*

PULSE SPECIES: electric organs discharge in short widely separated pulses; repetition rate usually low and widely variable; Mormyridae, some gymnotoids, e.g., *Electrophorus*, *Gymnotus*, *Hypopomus*; some skates, Torpedinidae, Malapteruridae, and Uranoscopidae

Sinusoidal - a smooth repetitive oscillation


STRONGLY ELECTRIC INTERMITTENT
Astroscopus
Torpedo
Malapterurus
Electrophorus
Gymnarchus
Eigenmannia
Apteronotus
wave fish
Gnathonemus
Raja
Gymnotus
pulse fish
WEAKLY ELECTRIC
Moller 1995

The electroreceptive fishes include taxa that are non-electric and electric.

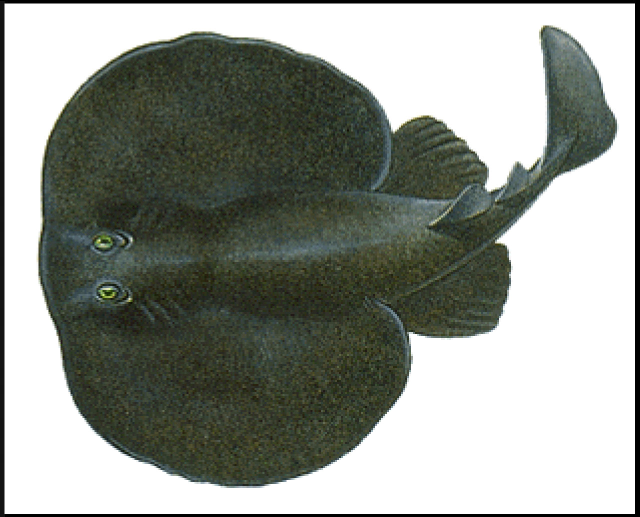
Non-electric forms may possess:

1. tuberous organs which are electrosensory – (eg. polypteroids, eels, lungfish and catfish)
2. Ampuli of Lorenzini (found in sharks and rays)

These are considered to be passive electrosensory systems because they only react to external electric stimuli.

Fish with active electrosensory systems provide electrical stimuli themselves (electrogenic fishes) and their own electroreceptors are sensitive to these.

These receptors can also react to external electric stimuli.



Detection of weak electric fields

Very basically, the events of electroreception is as follows:

1. An ELECTRICAL FIELD IS CREATED by an organism or the environment,
2. The SIGNALS CONVERGE ON THE RECEPTOR EPITHELIA of the receptor organ,
3. The receptor cells then CONVERT THE ELECTRICAL SIGNAL to a physiologically significant message which is transferred to the primary afferent nerves.
4. The nerves CONVEY THE SIGNAL TO THE CENTRAL NERVOUS SYSTEM where the brain analyses the signal, and the body responds accordingly.

Functions electroreceptors

PASSIVE MODE = detection of electric currents that ORIGINATE OUTSIDE of the fish's body

ACTIVE MODE = detection of fields GENERATED BY THE FISH ITSELF, EITHER by its ELECTRIC ORGAN or by its MOTION THROUGH THE EARTH'S MAGNETIC FIELD

Passive mode

PASSIVE used for prey detection

In elasmobranches and some catfishes. SHARKS, particularly hammerheads, can detect a flounder that are buried under 15cm of sand.

http://animal.discovery.com/videos/fooled-by-nature-hammerhead-shark-hunting-methods.html

PASSIVE used for communication

AMPULLARY ELECTRORECEPTORS play a role in INTRA- AND INTERSPECIFIC ELECTRIC COMMUNICATION. WEAKLY ELECTRIC MARINE SKATES communicate by means of an electric organ that EMITS LOW FREQUENCY DISCHARGES that are picked up by the ampullary receptors of individuals of the same species.

Active mode

The ACTIVE mode is for ORIENTATION

In the OCEANS, ELECTRIC FIELDS are generated by the FLOW OF WATER THROUGH THE VERTICAL COMPONENT OF THE EARTH'S MAGNETIC FIELD.

In other words, the MAGNETIC FIELD IS PERPENDICULAR TO THE SURFACE OF THE EARTH, and the water flows at 90° to it. Called MAGNETIC FIELD COMPASS

The interaction between the magnetic field and the movement of the water creates a MOTIONAL-ELECTRICAL FIELD.

Detected by ELASMOBRANCHS and informs fish about their drift with the water providing them with ORIENTATIONAL CUES during their movements in familiar territory.

In FRESHWATER, the fields are ELECTROCHEMICAL, and these fields are STRONGER than the MOTIONAL/ELECTRIC FIELDS IN THE SEA.

Detection of object location and communication signals: The AMPULLARY RECEPTORS of a fish are able to DETECT ITS OWN EOD's. This is called REAFFERENCE.

Besides being used in hunting, it allows the fish to DISCRIMINATE between their own EOD's, as well as those of other fishes, and serves as a way to communicate with conspecifics.

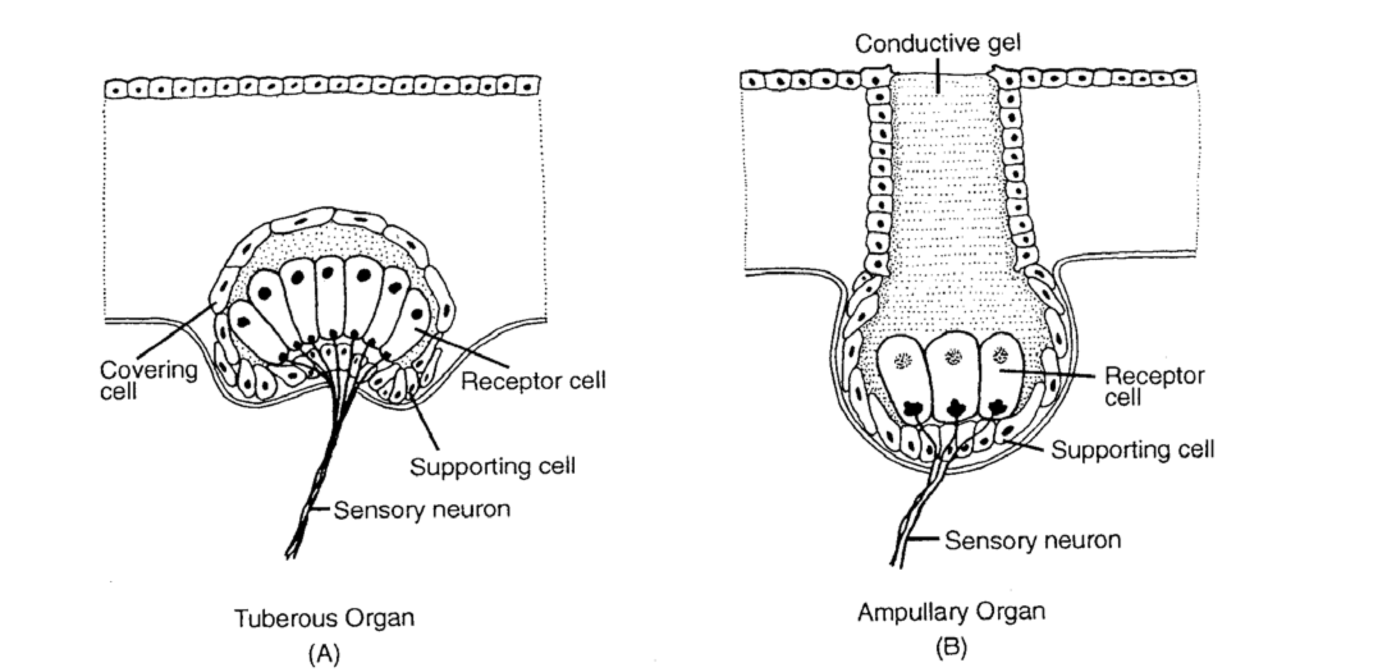
http://www.youtube.com/watch?v=kILqK3et8OQ

Structure of electroreceptors

The ELECTRORECEPTIVE CELLS are HAIR CELLS and similar to those of the MECHANORECEPTION SYSTEM.

The receptive cells can be organised into 2 types of receptor organs:

TUBEROUS RECEPTOR ORGANS AMPULLARY RECEPTOR ORGANS



Schematic diagram of the structure of tuberous (A) and ampullary (B) electroreceptive organs. Both organs are surrounded by layers of flattened cells that are tightly joined to one another. This helps prevent current from bypassing the organs. Tight junctions between the receptor cells and supporting cells help focus incoming electrical current through the base of the receptor cells, where they synapse with sensory neurons. Supporting cells in ampullary organs produce a highly conductive jelly that fills the canal linking the sensory cells to the surrounding water.

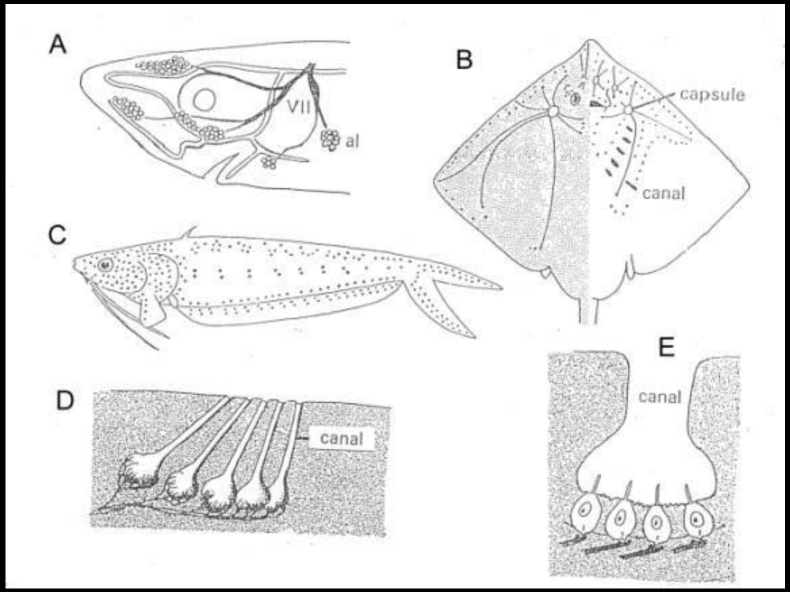
Ampullary electroreceptors

The AMPULLARY RECEPTORS organs are particularly SENSITIVE TO WEAK ELECTRIC FIELD GRADIENTS. Ampullary receptors are most capable of detecting frequencies below 50 Hz.

Despite the basic structure, there are several variations.

MARINE fishes → canal is LONG

FRESHWATER fishes → canal SHORT



The SKIN OF MARINE ELASMOBRANCHS has a LOW RESISTANCE, so ELECTRIC CURRENTS can PASS through it EASILY = VOLTAGE DIFFERENCE across skin is SMALL.

The SKIN OF FRESHWATER FISHES has a much HIGHER RESISTANCE, thus the voltage GRADIENT IS HIGH over short distances. Gradients can be DETECTED in SHORT CANALS

In freshwater fishes the longer canals ENHANCE THE FISH'S SENSITIVITY to voltage gradients,. This increases the distance between the surface of the fish, and the point of receptivity.

The receptor cells also exhibit morphological differences - NON-TELEOST CELLS have a KINOCILIUM, and SOMETIMES MICROVILLI at the apical end of the cell

TELEOST CELLS have only MICROVILLI.

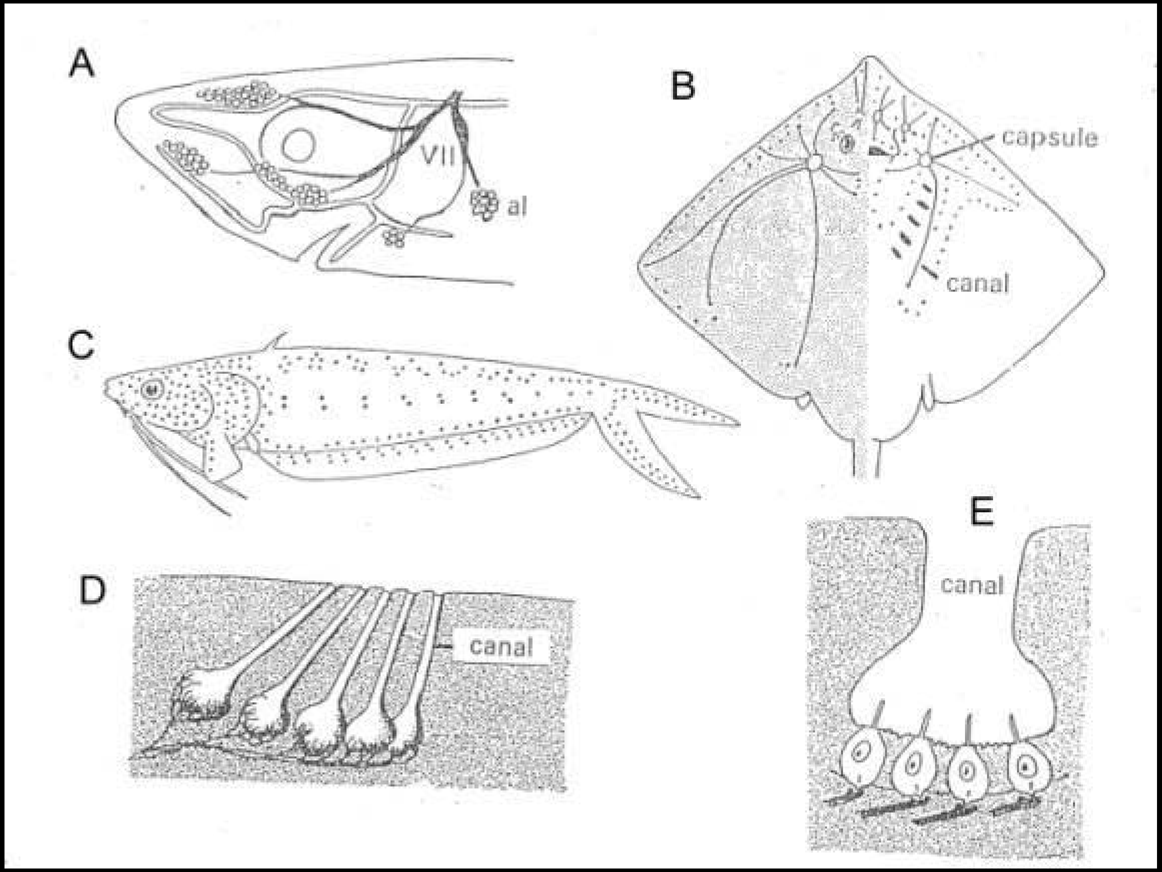


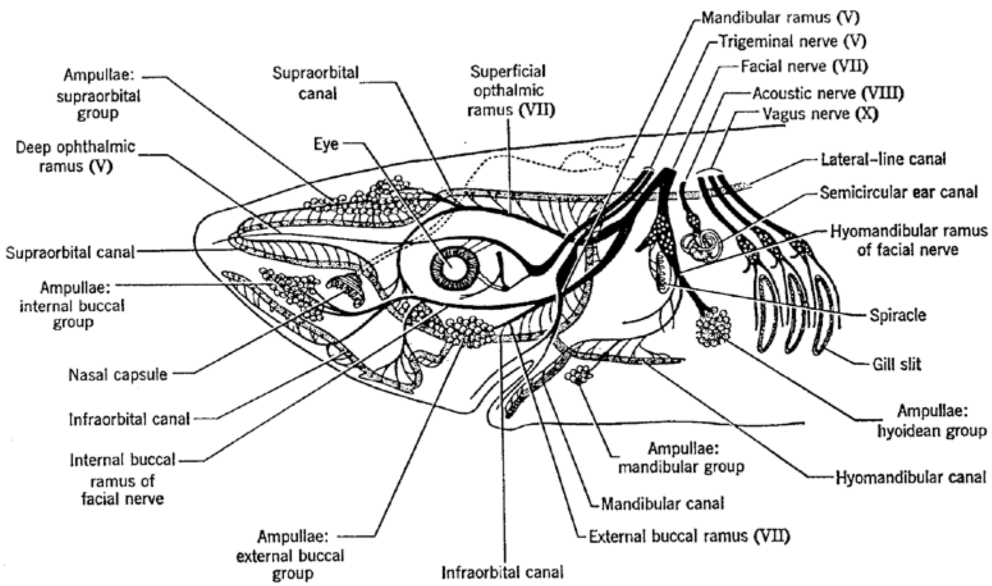
Figure 5.2: Ampullary electroreceptors; A) groups of ampullae (al) on the head of a shark; B) dorsal and ventral surfaces of a ray showing the openings of the ampullary organs and the canals into which they collect; C) distribution of ampullary organs on a catfish; D) groups of ampullary organs on the head of a shark; E) ampullary organ from the snout of a sturgeon.

The ampullary organs of ELASMOBRANCHES are called the AMPULLAE OF LORENZINI.

They are GROUPED TOGETHER IN SUBCUTANEOUS CAPSULES, usually CLUSTERED ON THE HEAD, but the CANALS CAN SPREAD and open in many directions over the ENTIRE BODY.

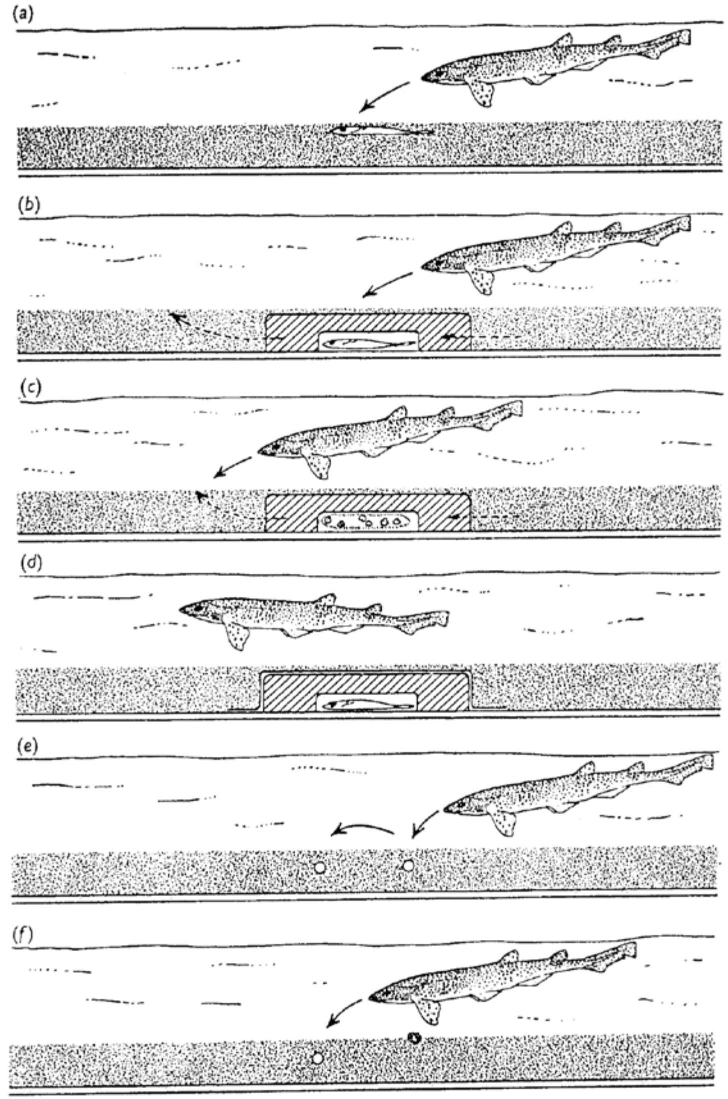
In addition, the DISTRIBUTION OF THE CANALS seems to be SPECIES SPECIFIC.

The DISTINCTION occurs in the NEURONS OF THE ELECTROSENSORY LATERAL LINE LOBE, the part of the lateral line that receives the electric stimuli.



Distribution of the ampullae of Lorenzini and sensory canals and their innervation in the head of shark

In this classic study, the **spotted dogfish** (*Scyliorhinus canicula*), feeding on juvenile flatfish (*Pleuronectes platessa*) that had taken refuge beneath the sand, was shown to ignore olfactory cues when electric potentials—produced in part by contracting respiratory muscles of the flatfish—were present. The shark even ignored visual cues in preference to electrical stimuli received by way of the **ampullae of Lorenzini.**



Feeding responses of *Scyliorhinus canicula* toward a flatfish (a), *Pleuronectes platessa,* under sand; (b) flatfish enclosed within an electrically transparent agar chamber; (c) pieces of fish in an agar chamber; (d) flatfish in an agar chamber covered with an electrically insulating plastic film; (e) electrodes simulating the bioelectric field of a flatfish; and (f) a piece of fish and an electric field. Solid arrows indicate responses of the shark; dashed arrows indicate flow of seawater through the agar chamber. After A. J. Kalmijn (1971).

Tuberous receptors

TUBEROUS RECEPTORS are located in an EPIDERMAL INVAGINATION into the corium.

These receptors are COVERED WITH SKIN, usually WITHOUT A CANAL opening to the skin surface.

The SPACE ABOVE THE RECEPTOR is, however, filled by LOOSE PLUG CELLS.

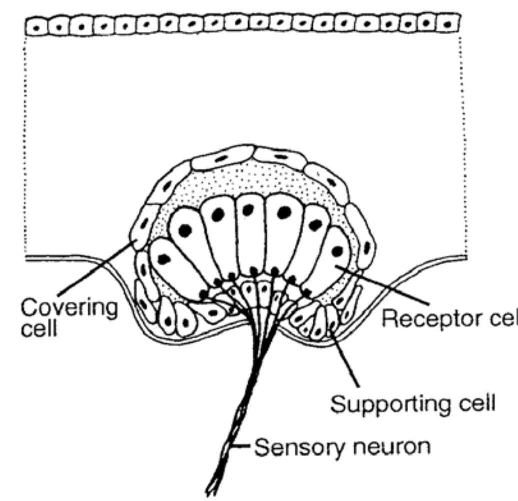
So, in essence, the there is a CHANNEL FOR THE ELECTRIC CURRENT FLOW across the skin.

The MORMYRIFORM and GYMNOTIFORM (knifefishes) fishes have developed electric organs that PRODUCE RHYTHMIC ELECTRIC FIELDS.

Electric fishes produce EITHER PULSE-LIKE or CONTINUOUS WAVE-LIKE EOD's (electric organ discharge).

The DURATION, SHAPE and FREQUENCY of the wave-like EOD's are SPECIES-SPECIFIC and POSSIBLY SEX-SPECIFIC.

These species have TUBEROUS RECEPTOR ORGANS that are fired specifically by EOD's (electric organ discharge).



Tuberous Organ
(A)

The ampullary receptors of the MORMYRIDS (the elephant fishes) can RESPOND TO THEIR OWN ELECTRIC ORGAN DISCHARGES (EOD).

This means that the fish needs to DISTINGUISH BETWEEN THEIR OWN DISCHARGES and CONSPECIFICS.

This allows the fish to IDENTIFY BOTH CONSPECIFICS and POTENTIAL MATES based on the EOD's alone. Most fishes that produce electricity use it for communication. The signals are SPECIES SPECIFIC, and aspects of the EOD can be changed. These include the amplitude, frequency, and pulse length.

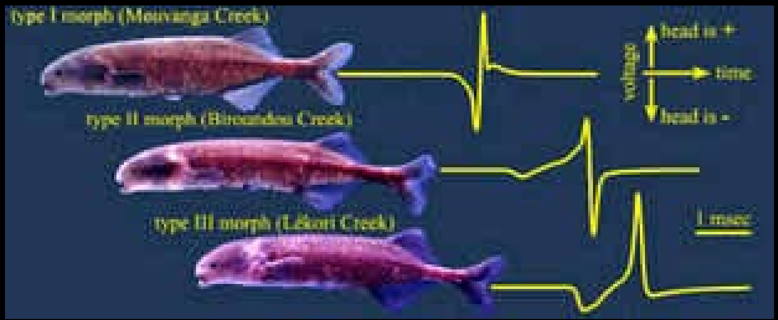
The AFRICAN ELEPHANT FISHES use EOD's in SPECIES AND SEX RECOGNITION, to WARN CONSPECIFICS and to MAINTAIN CONTACT WITH SHOAL

TUBEROUS RECEPTORS have a HIGHER FREQUENCY RANGE than AMPULLARY RECEPTORS but have REDUCED LOW-FREQUENCY SENSITIVITY

Some of these organs seem to TUNE INTO A ‘BEST’ FREQUENCY, at which their receptivity is maximum.

OTHERS are RESPONSIVE to a BROADER RANGE of frequencies.

In many cases, the ‘SENSITIVITY RANGE’ is an ADAPTATION to the properties of the fishes' OWN EOD's.

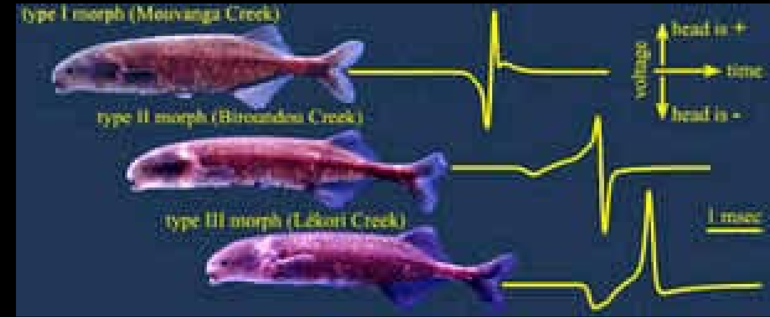


In the MORMYRIDAE, the tuberous receptors are called KNOLLENORGANE and MORMYROMASTS

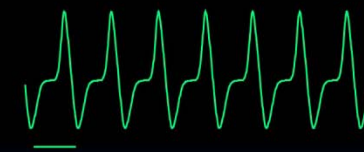
GYMNOTIFORMES may produce pulse or wave-like EOD's, and both types of fishes have 2 receptor types.

These units DIFFER in the NUMBER and LENGTH OF THE ACTION POTENTIALS in response to the stimuli.

Functions of tuberous electroreceptors



TUBEROUS ELECTRORECEPTROS have EVOLVED IN WEAKLY ELECTROGENIC TELEOSTS to detect their own EOD's, or those generated by their conspecifics and other electrogenic fishes.



Briefly, the functions of tuberous receptors are:

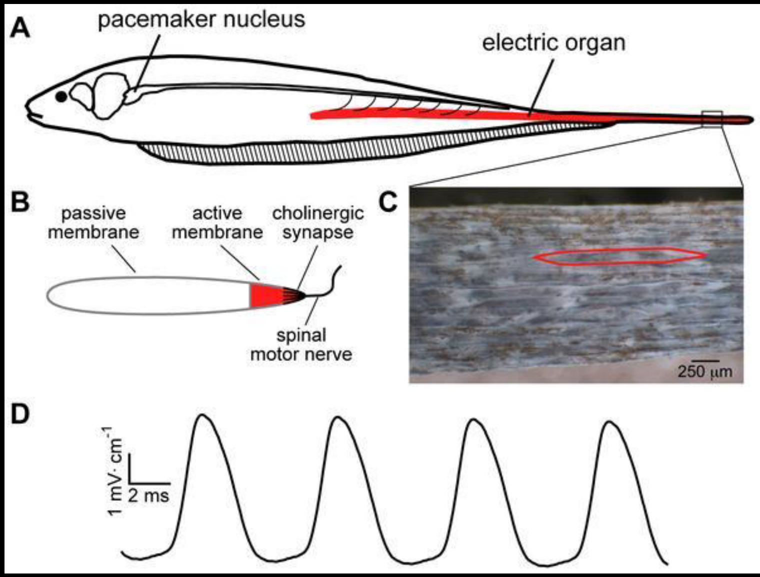
Sternarchorhynchus mormyrus (Steindachner, 1868)

ACTIVE OBJECT DETECTION,

to SUPPORT THE LOCATION STRATEGY by which other electric fishes might be found from a distance, the transmission of electric organ discharge displays, as received from other electric fishes.

Campylomormyrus phantasticus (Pellegrin, 1927)

ELECTROGENESIS



Some fishes that have specific organs that PRODUCE AN ELECTRIC FIELD OUTSIDE THE BODY.

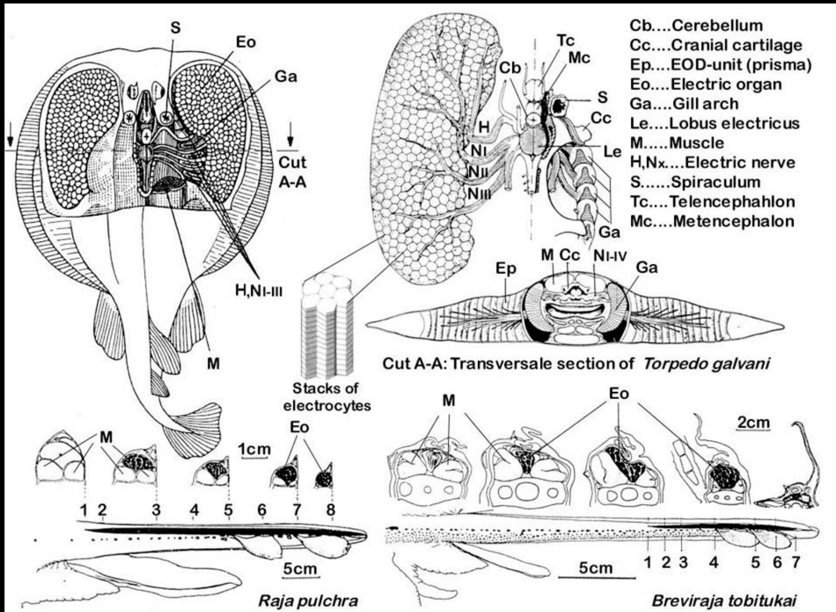
In most cases, these cells are MODIFIED MUSCLE CELLS

These ORGANS ORIGINATE from various muscles in DIFFERENT PARTS OF THE BODY – mormyrids on caudal peduncle and torpedinids in pectoral muscles.

Electrogenic fish - STRONGLY or WEAKLY ELECTRIC

BRIEF DISCHARGE – strongly electric for prey attack or defence

CONTINUOUSLY DISCHARGING organs are usually weak.

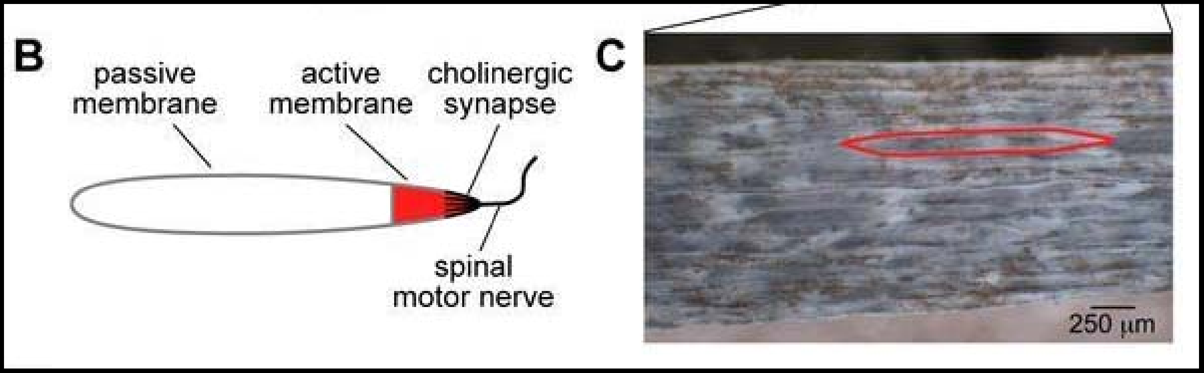


Organ structure

LIVING CELLS maintain an ELECTRICAL POTENTIAL DIFFERENCE across their membranes, with an OVERALL NEGATIVE CHARGE on the inside of the cell.

In ELECTROGENIC FISHES, the electric organs are usually made up of DISKLIKE MODIFIED MUSCLE CELLS or ELECTROCYTES.

Collectively, these cells are called ELECTROPLAQUES.



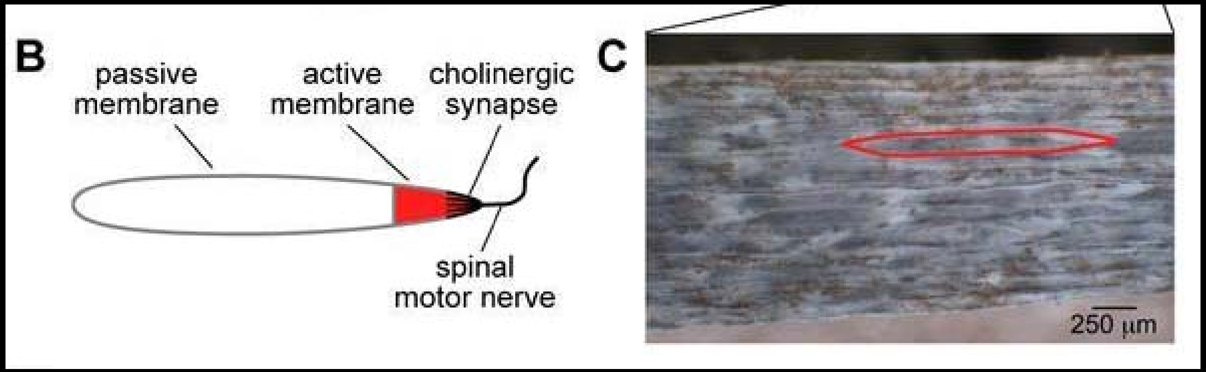
How is electricity generated?

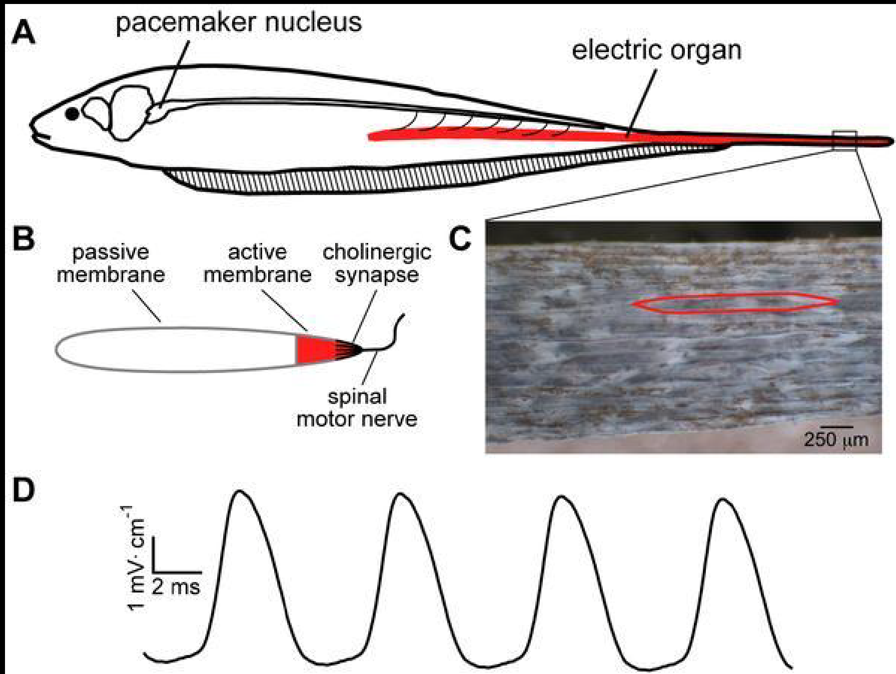
- When STIMULATED, the ION FLUX ACROSS THE CELL MEMBRANE creates a small electrical current.

- The cells of the electric organ are STACKED IN COLUMNS, and DISCHARGE SIMULTANEOUSLY, producing an ADDITIVE EFFECT.

- STRONGLY ELECTRIC FISHES have MONOPOLAR PULSE DISCHARGES

- WEAKLY ELECTRIC FISHES often have BIPOLAR WAVEFORMS



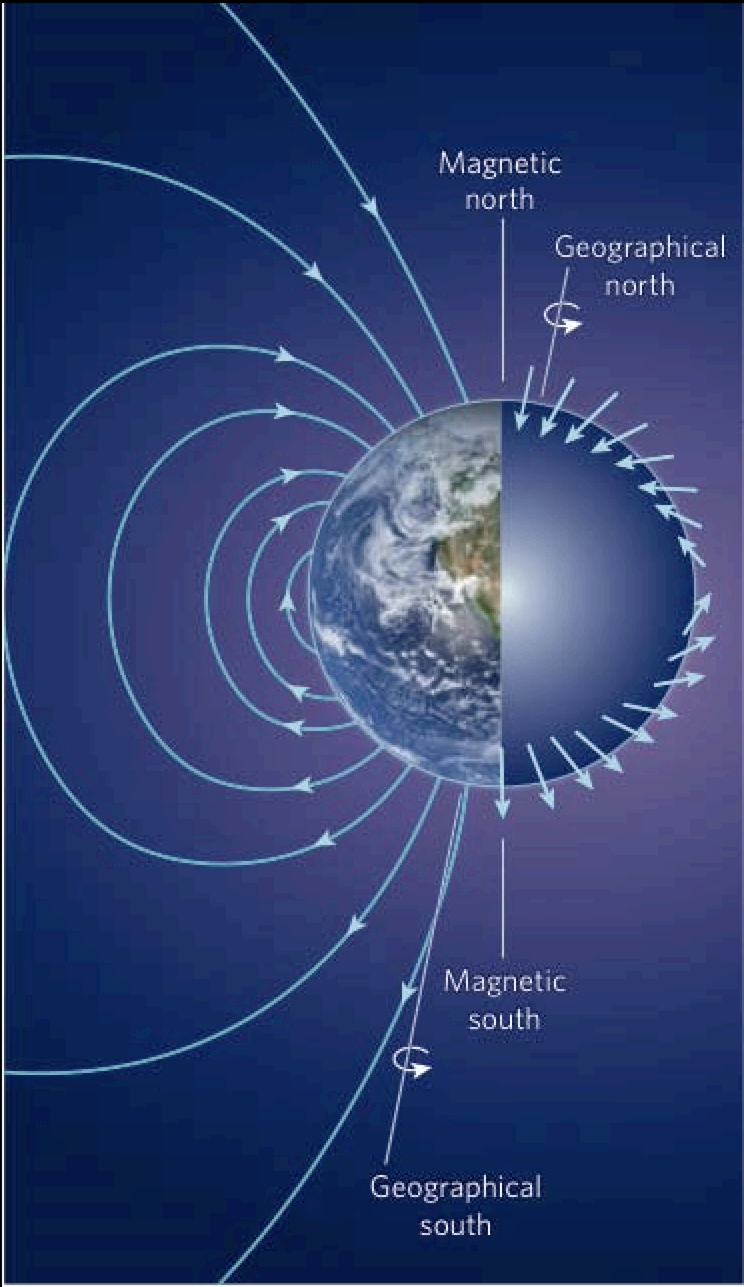


From the PLoS Biology paper: Electric fish generate electric organ discharges (EODs) by the simultaneous action potentials (APs) of excitable cells in the electric organ. (A) The EOD is produced by the coordinated APs of the electric organ cells, called electrocytes. A medullary pacemaker nucleus controls the electrocyte APs via spinal electromotor neurons which innervate the electrocytes. (B) Electrocytes are innervated on the posterior end of the cell, where the spinal nerve forms a large cholinergic synapse. The electrically excitable region of the cell membrane, populated by Na+ and K+ channels, is localized to the posterior most region of the cell, extending approximately 150 µm toward the anterior of the cell. The remainder of the cell membrane is electrically passive. APs in the electrocytes cause current to move along the rostral-caudal body axis and out into the surrounding water. (C) A section of electric organ from the tail, with skin removed to expose the electrocytes, which are densely packed within the electric organ. A single electrocyte is outlined in red. (D) The EOD waveform recorded from S. macrurus is a sinusoidal wave emitted at a steady frequency by each fish. The EOD frequency among fish has a range of approximately 70 to 150 Hz. (Credit: Michael R. Markham, M. Lynne McAnelly, Philip K. Stoddard, Harold H. Zakon. Circadian and Social Cues Regulate Ion Channel Trafficking. PLoS Biology, 2009;7(9): e1000203 DOI: 10.1371/journal.pbio.1000203)

Magnetoreception

Outline:

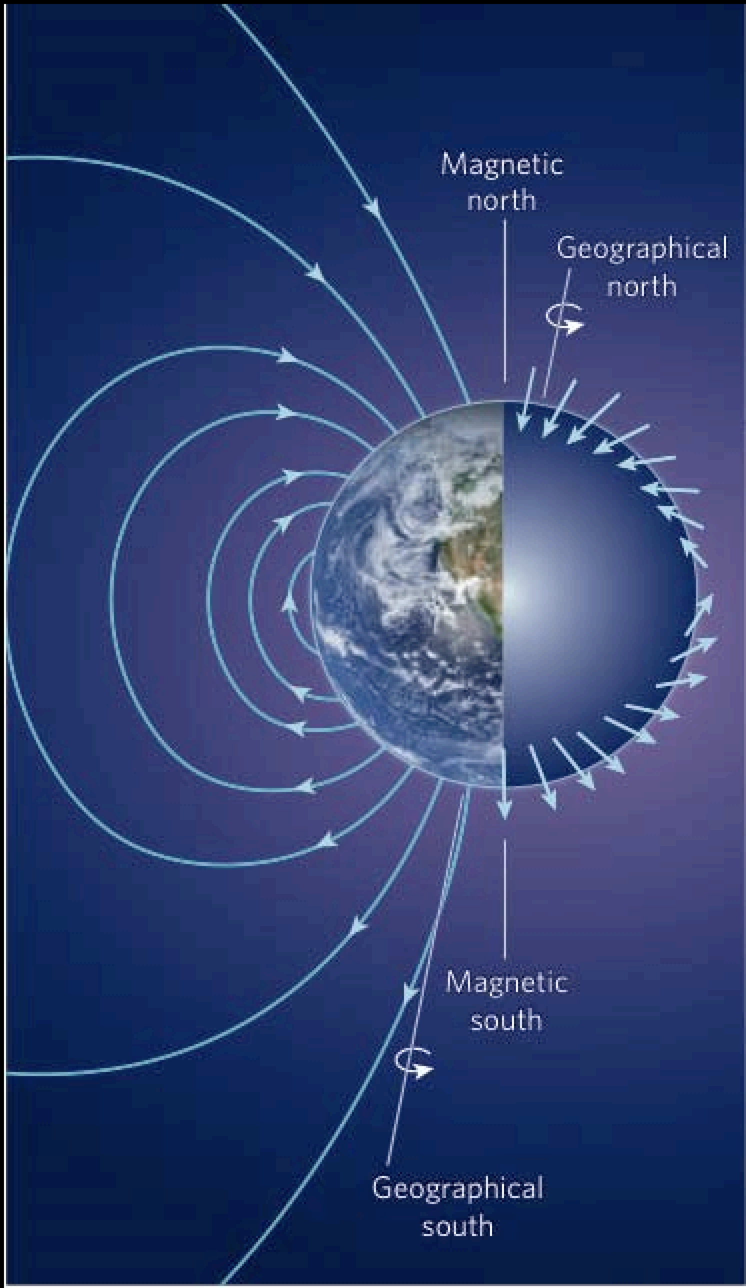
- Introduction
- Detection of magnetic fields
- Structure of magnetic receptors



Introduction

What is magnetic field detection?
Magnetoreception is the ability to perceive the Earth's magnetic field. This used to be dismissed as completely impossible, but now, we know that this ability is found in all major groups of vertebrates: this is the subphylum Vertebrata that we are a part of. The list of animals with magnetoreception includes flies, chickens, newts, lobsters, the European robin etc.

Earth's magnetic field?
Our planet has a magnetic field, in the same way that a di-pole magnet does. There are magnetic field lines that leave the southern hemisphere and curve around the globe and reenter the planet in the northern hemisphere(Look to picture 1). At each location on the globe, these same magnetic field lines intersect the Earth's surface at a specific angle of inclination. These angles are being represented on picture 1 on the right side of the globe, by the arrows at different angles. Picture 2 shows a close up of what I have just described, fish could hypothetically pick up on this inclination angle *as well as* the field intensity which is strongest near the magnetic poles and is weakest near the equator. In order for this to occur, salmon would have to imprint the magnetic signature of their natal region before leaving to sea, this imprinting could possibly occur similarly to olfactory imprinting. This makes the compass usable for navigation.



Introduction

- Unsurprisingly, fish use magnetorecption for migration
- Many fish MIGRATE in response to ENVIRONMENTAL CHANGES (temperature and food availability) or REPRODUCTION (salmon and angullids).

- The ALBACORE TUNA appears to follow the 14°C isotherm in the North Pacific. In HERRING, the northward migration in the North Sea is related to the increase in plankton blooms on which these fish feed.

- The BLUEFIN TUNA may also migrate across the North Pacific, in search of food.

- These fish all have an Amazing Ability TO FIND THEIR WAY BACK `HOME'.

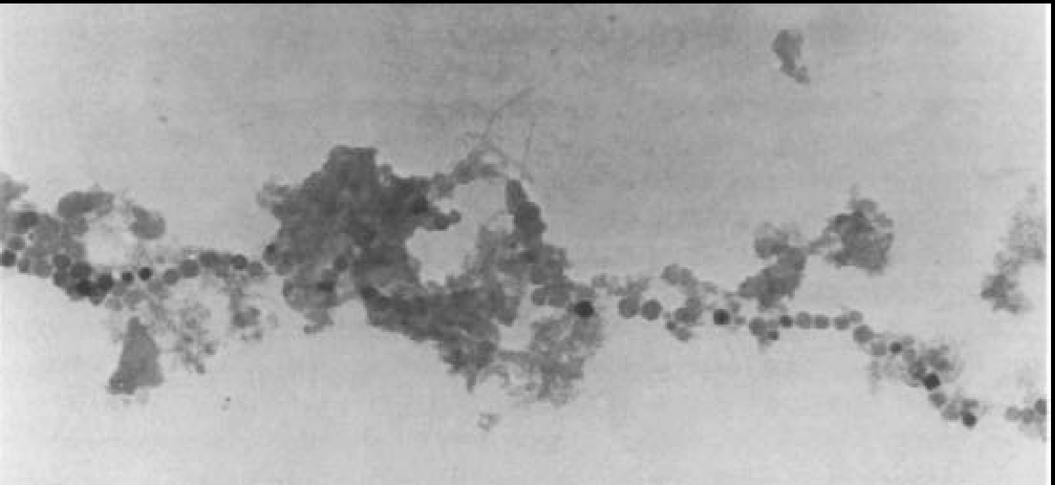
- Fish will use the EARTHS' MAGNETIC FIELDS to orientate themselves. These fields are quite weak, but are often strengthened by the electric fields generated by the movement of water through the magnetic field.

Detection of magnetic fields

- ELASMOBRANCHS can detect magnetic fields through the use of their AMPULLARY RECEPTORS.
- TELEOSTS, LACKING ELECTRORECEPTION are ALSO ABLE TO DETECT magnetic fields.
- The ferromagnetic mineral, called MAGNETITE, situated in tissue associated with the skull, functions as a BIOLOGICAL COMPASS.
- In salmon it has been PROPOSED that this COMPASS IS SET AT THE TIME WHEN THE FISH ENTERS THE OCEAN. The INFORMATION RETAINED is the VERTICAL AND HORIZONTAL COMPONENTS OF THE EARTH'S MAGNETIC FIELD at that point, as well as the difference between the magnetic and true north.
- These FACTORS will provide a combination that is UNIQUE FOR ANY GEOGRAPHICAL LOCATION.

Structure of magnetic receptors

- MAGNETITE has been found in the DERMETHMOID BONE OF THE SKULL and in other parts of the body, such as the GUT (European eel, the yellowfin tuna and the chinook and sockeye salmon).
- The material is made up of FINE GRAINED MAGNETITE that are produced as BIOCHEMICAL PRECIPITATES
- These PARTICLES ARE TOO SMALL to act as magnetoreceptor individually
- As a consequence, the PARTICLES ARE ORGANIZED INTO CHAINS that could easily ATTAIN THE SIZE REQUIRED for magnetoreception



Animals RESPOND TO THE MAGNETIC FIELD IN ONE OF TWO WAYS:

1. MAGNETIC FIELD DIRECTION, called the COMPASS RESPONSE, or to
2. SOME FEATURE RELATED TO INTENSITY, called the INFERRED MAP RESPONSE.

- Only a FEW HUNDRED CRYSTALS ARE NECESSARY to determine the direction of the geometric field.

- In contrast, the detection of MAGNETIC FIELD INTENSITY requires the ability to determine BOTH THE POSITION AND DIRECTION of the field requires millions of magnetite receptors.

- It has therefore been SUGGESTED the PRESENCE OF MAGNETITE in salmon is ACCUMULATIVE.

- This means that MAGNETITE IS PRESENT IN SMOLTS in QUANTITIES SUFFICIENT to provide them with the ABILITY TO DETERMINE MAGNETIC FIELD DIRECTION.

- End of lecture