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Electrogenesis, electrical discharge and storage in Pikachu

Rikesh Kunverji
Natural Sciences (Life and Physical Sciences), School of Biological Sciences, University of Leicester
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Abstract
Using Pokédex entries and electric eels as a model organism, this paper will discuss generation, storage and discharge of electricity in Pikachu. Due to its high voltage, generation of electricity using electrocytes alone is unlikely due to the unfeasible concentration gradient required. Electrocyte sodium channels are also likely activated by serotonin due to electrical discharge being dependent on the organisms emotional state. Pikachu cheek pouches store vast amounts of electrical energy and would likely require a capacitance akin to modern supercapacitors.

Keywords: *Computer Game; Anime; Biology; Electrogenesis; Pokémon; Pikachu*

Introduction
Pikachu is a well-known and beloved species of Pokémon within the popular Nintendo game franchise. In the anime series, the protagonist Ash also trains with a Pikachu as his first Pokémon. Pikachu is a small, murine creature with a long lightning bolt shaped tail, covered in yellow fur [1]. As an electric type Pokémon, it produces electricity on demand, and methods of how this is achieved will be explored in this paper based on analysis of Pokédex entries, the in-game encyclopaedia. Pikachu are also known to store electrical energy within the red circular pouches on each cheek [2], and the implications of this will also be discussed.

Figure 1 – The physiology of Pikachu. Features of note include the conductive fur and tail, and energy storing red cheeks [1].

Electrogenesis
The nervous systems of animals rely on the propagation of electrical impulses between neurons through the generation of action potentials. This is achieved through the influx of charged ions through channels on the surface of the cell. Through a similar manipulation of membrane potentials, electrogenic animals are able to generate their own electricity through the use of specialised electric organs, filled with cells called electrocytes. In electric eel electrocytes, a massive sodium influx takes the polarisation of the membrane from -85 mV to 65 mV [3]. Electrocytes are stacked in series, and with each electrocyte generating a potential difference of 150mV, this can quickly add up to produce a substantial voltage. In the case of electric eels, this has been measured to be several hundred volts [4]. However, the Japanese translation of the move 'Thunderbolt' literally translates to '100,000V Bolt', a discharge of a much greater magnitude.

$$\frac{Volume_{Eel}}{Volume_{Pika}} = \frac{\pi(0.07m)^2(2m)}{\pi(0.1m)^2(0.4m)} = 2.45 \qquad (1)$$

80% of the body of an electric eel is made up of electrocytes, for a total of 6000 cells [4]. Modelling the organisms as cylinders, Equation 1 shows the difference in size between the two organisms, emphasising the much greater density of electrocytes required in Pikachu, due to a body 2.45 times smaller. However, this calculation also does not include the tail, which may likely be exclusively filled with this type of cell. The potential gradient can be described by:

$$V = \frac{RT}{zF} \ln\left(\frac{[Na^+]_{out}}{[Na^+]_{in}}\right), \qquad (2)$$

the Nernst equation, where R is the ideal gas constant, T, temperature (assumed to be 37 °C), z, the ionic charge and F, Faraday's constant. To produce a potential difference of the order of 1 V in a single electrocyte, a ratio of extracellular to intracellular concentrations of 10^{15} is required. An increase of the sodium channel protein, $Na_v1.4$, [5] in comparison to electric eels alone is unlikely to cause this difference.

Discharge & Storage

Electrocytes are a derivative of muscle cells, which respond to the neurotransmitter acetylcholine (ACh) [6]. Evolution is an important mechanism in Pokémon growth, and Pikachu evolves from Pichu when it has reached a high level of happiness [1]. Discharge in Pikachu is also mood dependent [7], therefore it is reasonable to assume that instead of ACh being the neurotransmitter to activate the Na_v channels in Pikachu, serotonin is involved instead [8]. It is also assumed that the current produced by Pikachu can be modulated to a great degree, as Ash's Pikachu has electrocuted its trainer many times without major injury. However, despite being recognised as a 10 year old, Ketchum has performed extraordinary feats, such as effortlessly picking up and running with a Larvitar, a Pokémon known to weigh over 70 kg [9].

The signature move of the Pikachu evolutionary line is the aptly named 'Volt Tackle', and is the strongest physical electric type move in Pikachu's arsenal [2]. In the series of games, this attack is described in the as: 'the user electrifying itself, and then charging at the target' [7].

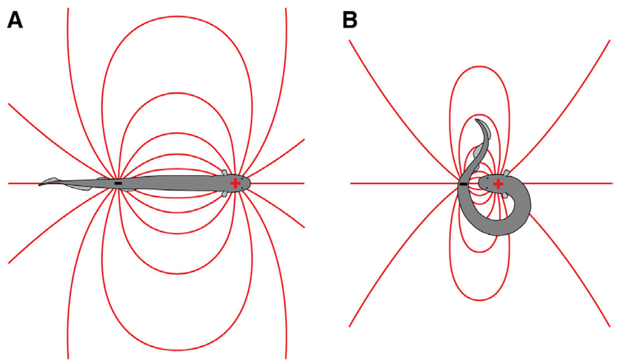

Figure 2 – Adapted from [10], a possible mechanism to explain the strength of Pikachu's physical attacks by concentrating the electric field, thereby amplifying the discharge.

As shown in Figure 2, the idealised electric dipole within electric eels can be changed in configuration by bringing head and tail closer together, in turn concentrating the density of electric field in a smaller area, amplifying the discharge [10]. If the current in Pikachu's electric organ flows from head to tail (or vice versa), the relative strength of this 'bull-rush' can be explained by the concentration of the electric field on contact with the target, when Pikachu is oriented correctly.

Due to the ability to discharge tens of thousands of volts, Pikachu's cheek pouches likely possess a high capacitance. Modelling the cheeks as a parallel plate capacitor, the charge stored is inversely proportional to the distance between them [11]. Modern supercapacitors utilise the electrostatic double layer effect to produce an atomic monolayer between plates, acting as a dielectric. If Pikachu cheek pouches comprise a material with high permittivity and angstrom-sized pores, similarly high capacitance can be achieved [12].

Pikachu tails behave as a lightning rod often being struck when being raised while Pikachu scouts its surroundings [13]. Whilst generation by electrocytes would likely represent the most consistent source of electrostatic energy to store, lightning strikes may also serve as another energy source. Realistically, the majority of this energy must follow a lower impedance path to the ground, rather than follow the path across Pikachu's electric organ. In electric eels internal resistance has been measured to be 450 Ω [14], and if this of a similar level in Pikachu, then the magnitude of Ohmic heating when directly storing the energy of a lightning strike would prove fatal.

Conclusion

High voltages in comparison to terrestrial organisms, makes generating electricity solely using electrocytes unlikely in Pikachu. Whilst a higher density of $Na_v1.4$ would increase the capacity of its electric organ, a theoretical ion concentration gradient ratio of 10^{15} would be biologically unfeasible. The relationship between emotional state and electrical discharge also suggests that serotonin, rather than ACh, gates ion channels. Finally, discharging thousands of volts requires Pikachu cheeks to have a high capacitance, and further study of their nanostructure, as well as the nature of the biological dielectric used will be of great interest for future technological applications.

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