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Playing an Electron Transport System Game to Improve Health Students' Learning

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Ⓢ *Supporting Information*

ABSTRACT: Understanding how the electron transport system makes ATP from the transfer of electrons by coenzymes is improved when students play a hands-on electron transport system game. The game requires students to play the parts of the electron carriers and coenzymes, demonstrating where and how electrons move through the system. This game looks at the big picture of what is occurring in the ETS and is intended for prenursing and predietetics students in a one-semester organic and biochemistry (OB) course or a one-semester general, organic, and biochemistry course (GOB). Many institutions offer these types of courses and the students need to have a good understanding of biochemistry to succeed in the health related professions.

KEYWORDS: *Second-Year Undergraduate, Biochemistry, Nonmajor Courses, Student-Centered Learning, Collaborative/Cooperative Learning, Humor/Puzzles/Games, Hands-On Learning/Manipulatives, Metabolism*

■ INTRODUCTION

The electron transport system (ETS) is one of the major components of the process of cellular respiration. Understanding how oxidative phosphorylation makes many more ATPs per mole of substrate than substrate-level phosphorylation is an important part of understanding both the concept and the evolution of cellular respiration. During oxidative phosphorylation, the ETS works by creating an electrochemical gradient through proton movement across a membrane. This proton gradient is a pool of potential energy that will power an ATP synthase protein, producing the ATP necessary for most metabolic reactions. Because of the nature of the reaction, it can be difficult for some students to visualize how the movement of electrons and hydrogen ions can allow for energy production. Many students have difficulty in picturing anything on the molecular scale since they cannot directly interact at that level.[1] Students, however, need to understand biochemistry and the biochemical functions of such systems because they provide background information for the next set of courses specific to the health related majors.

Many colleges and universities offer either a one-semester GOB (general, organic, and biochemistry) course or a one-semester organic and biochemistry (OB) course for preprofessional students. In these courses, the amount of biochemistry presented is limited due to time and content needs, but certain concepts, such as cellular respiration, must be understood.[2]

Educational games have the advantage of engaging students by their using auditory, visual, and psychomotor learning styles all at the same time.[3] This method can enhance their learning along with making learning more interactive and fun.[3] Games often are used to give students another opportunity to see information in a different format.[3] One advantage of using games is that students are more excited to play a game than listen to a lecture and it can get them excited about material they would not otherwise think was interesting.[4] Even if students do not improve their understanding of a topic as measured by standard assessments using a game, the fact that they are engaged in the material, sharing information with peers, and having fun may be an advantage in increased retention.[3,4] Other researchers state that their students were more open to learning because games are nonthreatening, fun, and interactive.[5,6] Educational games improve student learning by improving student critical thinking, problem solving, and creativity.[6] Some disadvantages to using games are that they take time to play, they usually are not done in very large classroom settings, and they take time and energy to set up initially.[4]

This role-playing game was developed for such a combined organic and biochemistry course intended for prehealth and predietetics majors to demonstrate oxidative phosphorylation. The primary learning objective addressed by this game is that students can describe how an ETS can be used by a cell to generate ATP.

The number of available games at the appropriate level is limited, though several are available online.[7,8] One published by Kathleen Cornely is a game for biochemistry for science majors[7] and includes more information than either an OB or GOB course would require. The game described here is deliberately general, but is intended for college undergraduates in preprofessional courses. It would also be appropriate for first-year introductory biology courses. The game's purpose is to demonstrate how an electrochemical gradient can be formed and used to generate ATP using an ATP synthase. The electrochemical gradient in particular is a concept that is typically difficult to grasp through lecture and readings for these student populations. Using a game simulation allows students to be part of the ETS and understand its complexity. Students given a pre- and post- self-assessment felt that they understood the ETS better after playing the game (Figure 1). Additionally, when a pre- and post-concept assessment of this game was done, there was a statistically significant difference in the

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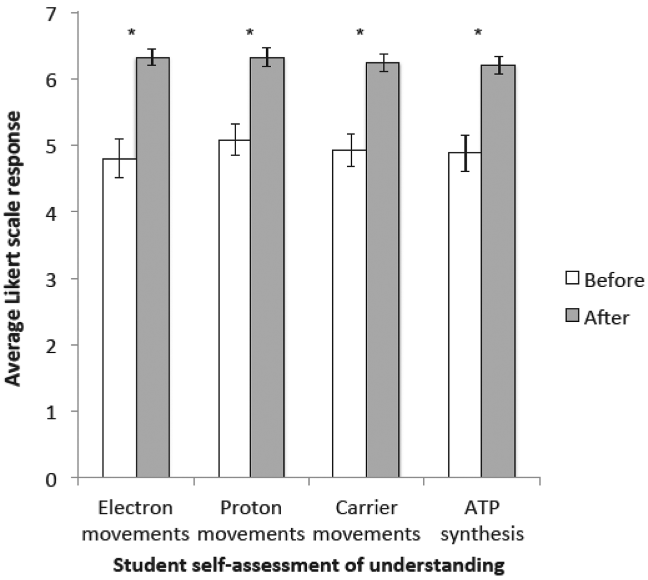

Figure 1. Student self-assesement of understanding the electron transport system after playing the ETS game (paired t tests, $p < 0.001$, $N = 25$ students). Error bars are standard error.

understanding of the ETS after playing the game than before playing the game (Figure 2).

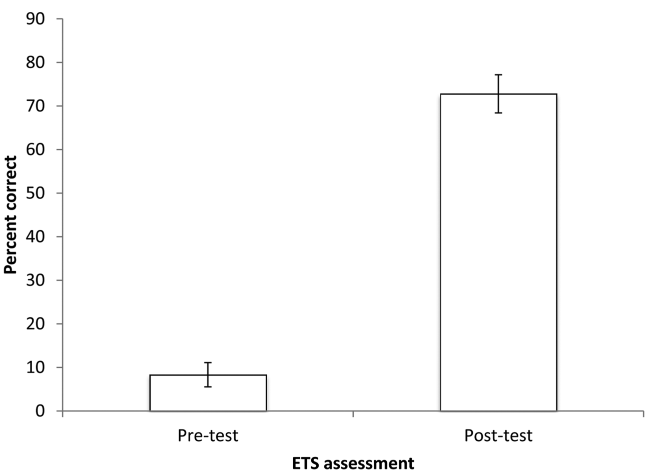

Figure 2. Comparison of student understanding of the ETS before and after playing the ETS game. In a paired t test, there was a significant difference between the pre and post assessment of the student understanding of the ETS ($t = 13.245$, df = 17, $p < 0.001$). Error bars are standard error.

The game is set up for 10−14 students and has been done in a laboratory setting. However, it could be played in a large classroom with more students using multiple ETS set-ups, similar to what occurs in a cell. This game takes about half an hour to an hour to play three times through with students changing roles. The specific times depend upon the questions of the students and the amount of prompting needed by the instructor.

General Description of ETS Used for This Game

When one glucose molecule is degraded in the human cell, it produces two ATP's from substrate-level phosphorylation in glycolysis and two are produced as GTP in the citric acid cycle, also a substrate-level phosphorylation reaction. Many more ATPs are generated via the electron transport system. Electrons are transferred from various molecules during glycolysis, the intermediate reaction, and the citric acid cycle by redox reactions to two coenzymes, NAD^+ and FAD. These are reduced to NADH and $FADH_2$. The NADH and $FADH_2$ generated by those reactions will donate their electrons to the ETS, which is composed of electron carrier molecules embedded in the inner mitochondrial membrane. The ETS allows movement of hydrogen ions against their concentration gradient using the transfer of these electrons to provide the energy needed.

The hydrogen ion gradient formed by this process then is used to make ATP via a large inner membrane protein, ATP synthase, which allows the hydrogen ions to travel back down their gradient into the mitochondrial matrix, harnessing the energy released to make ATP. Electrons that have been transferred to the end of the system are accepted by oxygen to make water.

Basic Game Components

The game consists of six stations along a table representing the inner membrane and the electron carrier complexes. These could be six individual desks in a lecture hall as well. Baskets or boxes can be used to represent the complexes (so "electrons" and "hydrogen ions" cannot be dropped or roll away), but paper or cardboard signs would work as well. One side of the table represents the matrix of the mitochondria and the other side is the intermembrane space. The roles of student players are Complex I, Complex II, Complex III, Complex IV, and ATP synthase at fixed stations, and NADH, $FADH_2$, coenzyme Q, cytochrome c, hydrogen ions, and oxygen as mobile players (Table 1). We have found name tags or lanyards with the roles printed on them allow students to remember their roles more easily. The game also requires tokens representing electrons and hydrogen ions to be passed by students as electron transport progresses. Plastic golf balls, plastic Easter eggs, poker chips, or similar tokens can be used, though there need to be two distinct types to represent electrons and hydrogen ions, respectively. We have used the plastic Easter eggs as hydrogen ions, so we can place fake paper money to represent the ATP produced as energy "currency" by the ATP synthase (Table 2). This metaphor is commonly used in biochemistry and allows students to recognize energetically expensive reactions readily. Again, some other representation would work as well. The specific steps of the game are in the Supporting Information.

Table 1. Roles and Number of Students

Roles	Number of Students
NADH	1
$FADH_2$	1
Coenzyme Q	1 or 2
Cytochrome c	1 or 2
Hydrogen ions	2
Complex I	1
Complex II	1
Complex III	1
Complex IV	1
ATP synthase	1 or 2
Oxygen	1 or 2

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Table 2. Props Needed

Role	Prop Needed
Complexes I–V	6 containers or stations
Four Electrons	2 for NADH and 2 for $FADH_2$
Ten hydrogen ions	2 in Complex I, and 4 each (two for NADH and two for $FADH_2$) in Complexes III and IV
Four hydrogen ions to add to oxygen to make water	These are given to each molecular oxygen making 2 water molecules (there is 1 water molecule made for each pair of electrons transferred)
ATP (optional)	This ends up in ATP synthase
Inner mitochondrial membrane	Some type of table or barrier

RESULTS AND DISCUSSION

The students are asked to describe the process of the ETS in making ATP using cellular respiration by filling in a worksheet as a guide. The worksheet reviews the electron carrier, hydrogen ion, and electron movements across the ETS. It is emphasized that oxygen in aerobic respiration receives the electrons to form water with hydrogen ions.

Students self-reported improvement in their understanding of the ETS after playing this game (Figure 1). They reported a greater knowledge of the entire process along with how the electrons moved from complex to complex by the different electron carriers and how the ATP is made by the ETS. The questions used are in the Supporting Information.

Students were given a pre- and postconcept assessment of their understanding of the ETS. These assessments were a set of identical questions (also listed in the Supporting Information). After playing the game, students scored statistically significantly higher on the assessment than before playing the game (Figure 2). Although this does not compare the game to another method of learning, it does show that students do learn about the ETS while playing this game.

A basic understanding of how the ETS works to make ATP is the most important learning objective for an OB or GOB student. The other important learning objective is the fact that using the ETS makes a lot more ATP than substrate-level phosphorylation, which is necessary for large aerobic organisms like humans.

ASSOCIATED CONTENT

Supporting Information

Play-by-play steps in detail; questions used to assess students; suggested materials for this game. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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