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Understanding diffusion theory and Fick's law through food and cooking

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Zhou L, Nyberg K, Rowat AC. Understanding diffusion theory and Fick's law through food and cooking. *Adv Physiol Educ* 39: 192–197, 2015; doi:10.1152/advan.00133.2014.—Diffusion is critical to physiological processes ranging from gas exchange across alveoli to transport within individual cells. In the classroom, however, it can be challenging to convey the concept of diffusion on the microscopic scale. In this article, we present a series of three exercises that use food and cooking to illustrate diffusion theory and Fick's first law. These exercises are part of a 10-wk undergraduate course that uses food and cooking to teach fundamental concepts in physiology and biophysics to students, including nonscience majors. Consistent demonstration of practical applications in a classroom setting has the potential to fundamentally change how students view the role of science in their lives (15).

active learning; laboratory activity

DIFFUSION plays an essential role in our daily lives. It can be observed in a splash of perfume gradually scenting a room or a drop of ink bleeding onto a page. Thermal diffusivity is essential in the transfer of heat from the stovetop to a pan. To describe how the spontaneous movement of solute particles is driven by a concentration gradient, Fick's first law of diffusion provides a physical explanation, as follows:

$$J = D\frac{\mathrm{dC}}{\mathrm{d}x} \qquad (1)$$

In this one-dimensional simplification of Fick's first law, J is the solute flux, expressed as net moles of molecules flowing through a cross-sectional area per unit time perpendicular to the x-axis (in mol/m^{2}s); D is the diffusion coefficient (in m^2/s); dC is the difference in solute concentration (in mol/m^3); and dx is the characteristic length scale of the system (in m) (6).

This simple formulation of Fick's first law can describe numerous complex phenomena in the context of food and cooking: plant growth and ripening is triggered by the diffusion of small molecules such as ethylene, brining and marinating rely on the diffusion of salt and sugar molecules into meat, and dehydration occurs due to the diffusion and evaporation of water molecules from a food. Even the changing moisture profiles across a spaghetti noodle as it hydrates during cooking can be predicted using Fick's first law (9).

Such food-based phenomena provide tangible, real-life examples of diffusion; the connection can also be extended to understand how diffusion underlies other sophisticated scientific concepts. For example, a concentration gradient drives mass transfer, an electrical gradient determines the flow of electrons, and a temperature gradient underlies heat transfer. In fact, it was the application of Fourier's law of heat conductance to diffusion that first inspired Adolf Fick to develop his namesake law. As a 26-yr-old physician in 1855, Fick offered the following critical insight into the pioneering work of Thomas Graham, a contemporary who had developed his namesake law of effusion 9 yr earlier (7):

> A few years ago, Graham published an extensive investigation on the diffusion of salts in water . . . It appears to me a matter of regret, however, that in such an exceedingly valuable and extensive investigation, the development of a fundamental law, for the operation of diffusion in a single element of space, was neglected, and I have therefore endeavoured to supply this omission.

While Fick's law is central to everyday phenomena, it is remarkably nonintuitive for students, especially nonscience majors who may have an inadequate understanding of diffusion and osmosis (11, 13). In particular, the concepts of how particles move from a high concentration to a low concentration and why water moves against a solute gradient can be challenging for students to grasp (8). To address these gaps in understanding, more effective teaching methods are needed.

Food can be a useful vehicle for teaching scientific concepts (5, 14, 16). In this article, we present three simple exercises involving traditional and modern cooking techniques to illustrate diffusion and Fick's law to undergraduate students in a classroom setting. Specifically, we have used these exercises to convey the concept of diffusion in an undergraduate course for nonscience majors; the course was adapted from a previous class we developed (14) and covers physical concepts in physiology, including energy, diffusion, elasticity, viscosity, and binding affinity. These exercises on diffusion and Fick's law address concepts that are challenging for nonscience majors to grasp, such as the role of surface area and how the diffusion rate depends on the concentration gradient.

Applying Fick's First Law to Save Time When Making Flavorful Soup Stock

To impart an intuition for the role of surface area in diffusive processes, a simple example focuses on making soup stock. Traditional methods call for simmering meat and vegetables for many hours to extract the maximal flavor. For example, a popular recipe instructs the cook to place 4 lb of chicken carcass pieces in a large water-filled stockpot together with one quartered onion and some halved carrots, celery, and leek and then to simmer uncovered for 6–8 h (4). To reduce cooking time, a more recent recipe suggests to "chop small to chop time"; a food processor can diminish vegetables to a very fine dice (12). The instructions proclaim that the resultant stock can become equally flavorful within as little as 2 h. We use Fick's first law to explain why this small dicing method works: by increasing the area of the vegetable-water interface, a greater number of molecules can diffuse into the stock per unit time; the larger interface and smaller dice effectively increases dC/dx (*Eq. 1*). Consequently, J increases, which means that the stock

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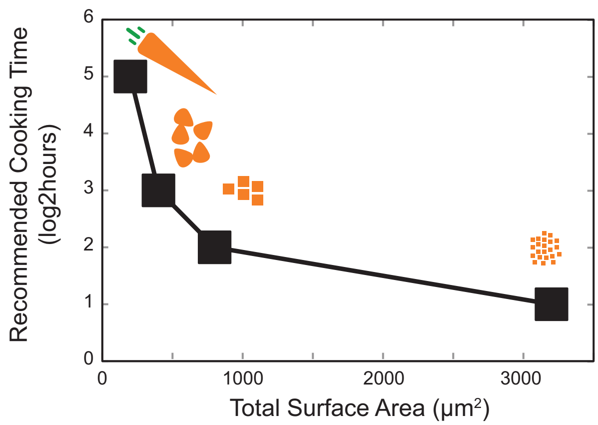

Fig. 1. Schematic showing cooking time as a function of carrot piece size.

achieves the same level of flavor within a shorter period of time. For example, by chopping a carrot of a given volume into increasingly smaller pieces, over a 10-fold increase in total surface area can be achieved, as shown by simple geometric considerations (Fig. 1).

Diffusion in Modernist Cooking: Spherifying Liquids

In modernist cooking, spherification is a popular technique that delivers food in unexpected shapes and forms (1). Using this method, liquids such as olive juice can be formed into a self-containing sphere so that a liquid center of juice is sealed within a membrane that consists of a polysaccharide gel; this results in olive "caviar." Alginate, a polysaccharide derived from brown algae, is an essential ingredient in spherification: it is added to a base flavor solution that can range from olive juice to raspberry puree to sea water (Fig. 2). Droplets of the alginate-flavor solution are then deposited into a bath of divalent cations, such as calcium chloride; the dissociated cations cross-link with the negatively charged alginate polymer chains, resulting in a self-enclosed sphere of the flavored liquid solution.

Since the concentration of calcium ions (1% calcium chloride by weight) in the bath is larger than the inherent concentration of divalent cations in the flavored solution, there is a resulting flux of calcium ions into the flavored puree-alginate solution; the divalent cations cause gelation (2). Using the simple theory for diffusion in one dimension, $\Delta x = 2Dt$, the thickness of the polysaccharide shell (Δx) can be predicted based on the diffusion constant of calcium in water (D; equal to 1.5×10^{-13} cm^2/s) and the length of incubation time (t) in the bath. Here, we chose units to represent tangible length and timescales that students can measure simply with a handheld ruler and timer. This enables students to conceptually connect the equation of the week and their observations, which aids in helping students to build a stronger intuition about diffusion. Interestingly, these theoretical results can be related to the observations and commentary of Chef Ferran Adrià, who

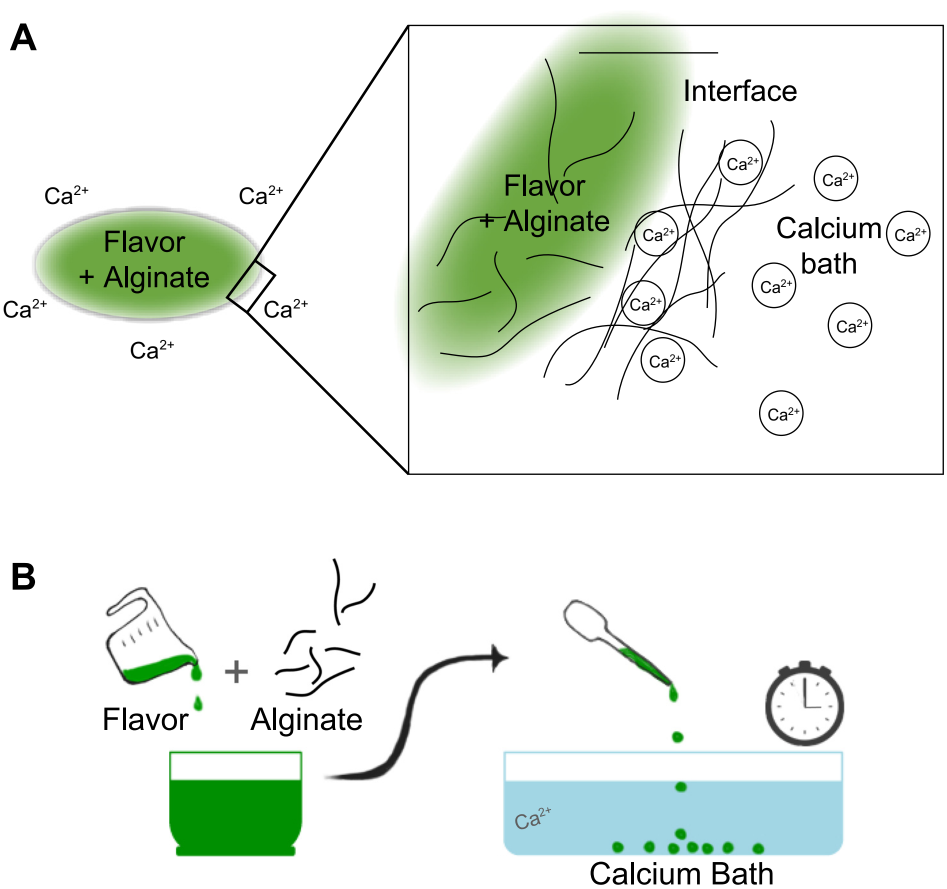

Fig. 2. *A*: schematic of the spherification procedure. For more details, see APPENDIX 1: SPHERIFICATION RECIPE. *B*: binding between alginate and calcium ions within a droplet of flavored liquid that is incubating in a calcium bath. Cross-linking first occurs at the interface between the flavored alginate droplet and the calcium bath as calcium ions diffuse into the flavored droplet.

Fig. 3. Materials required for calculating the diffusion coefficient using a mushroom-water system. Clockwise from *top left*: kosher salt, mushroom, jewelry scale, and ruler.

suggests incubating the alginate droplets in the calcium bath for "no more than a few minutes" (3). A simple calculation of shell thickness after a few minutes (t = 180 s) in the calcium bath yields Δx = 0.7 mm; a longer incubation of 10 min yields Δx = 1.3 mm. Considering that the diameter of a spherified caviar is ~2–4 mm, the short incubation time of a few minutes is crucial to maintain a liquid core. While this simple calculation relates well to the entertaining video featuring Chef Adrià, this exercise can also be extended to include Fick's law, where $dc = c_2 - c_1$ = 0.05 mol/l − 0.001 mol/l = 0.004 mol/l, where c_2 is the calcium concentration in the bath and c_1 is the typical calcium concentration in the flavored alginate solution.

Spherification is an inexpensive and simple exercise that can be performed in a laboratory or classroom setting: students can spherify a range of liquids, measure the thickness or mass of the shell, and relate their data to theoretical calculations based on Fick's law (see APPENDIX 1: SPHERIFICATION RECIPE).

Salting Mushrooms to Calculate the Diffusion Coefficient of Water

Salting and dehydration are common methods of conserving vegetables, fruits, and meats. During these processes, foods typically undergo a dramatic decrease in mass, which is mostly due to an efflux of water molecules. Fick's first law provides a quantitative framework for understanding the rate of water loss. As an inexpensive experimental system, we discovered that submerging a mushroom in a salt water solution provides a compelling demonstration, as it undergoes an observable loss of mass within <1 h. As described by Fick's first law, the rate of water efflux depends on *1*) the total surface area of the mushroom piece, *2*) the concentration of salt in the solution versus in the mushroom, and *3*) the smallest dimension (dx) of the mushroom piece. Thus, with careful observation and relation to Fick's first law, the diffusion coefficient of water can be determined within an hour. Importantly, this experiment requires just a few common pieces of equipment and can be performed in a classroom or home setting. One of our students even carried out this experiment on a table at a local coffee shop. To convey the creative process of experimentation in science, this laboratory exercise can be modified so that students can choose the variable they modify; for example, students may choose to explore the effect of different salt concentrations or the dehydration of mushroom pieces with different surface areas.

MATERIALS

Students are provided with a ruler, an inexpensive jewelry scale (Amazon.com, AWS-600-BLK, $10.29), kosher salt, and one to three large white button mushrooms (Fig. 3). The dimensions of a mushroom piece, which decrease over time during shrinkage, can be measured using a ruler. Alternatively, quantitative image-analysis software, such as free to download ImageJ (National Institutes of Health), can be used to determine mushroom dimensions based on images taken on a cell phone or digital camera by the student.

Methods for Student Instruction

In this exercise, you will determine the diffusion coefficient of water using Fick's first law by observing the decrease in mushroom mass over time that results from a gradient of salt ions.

To prepare the salt solutions, place the salt and water in small jars or cups to final concentrations of 5 g NaCl/100 g water and 10 g NaCl/100 g water. Swirl the solutions to dissolve the salt. As a control, use pure water. Peel and cut the mushroom caps into pieces that are ~3 × 1 × 1 cm.

First, record the initial mass of the mushroom pieces and determine their surface area; this can be achieved by measuring the mushroom dimensions using either a ruler or by acquiring images of the mushroom pieces and using quantitative image analysis. During image acquisition, position the mushroom by a coin to enable calibration of the length scale during subsequent analysis.

Next, place each mushroom piece into one of the two salt water solutions. To ensure that the mushroom pieces remain submerged, place a utensil or weight on top of the mushroom piece. (Two forks positioned so their tongs intertwine to provide a cage around the mushroom piece is an effective solution.). Remove the mushroom pieces at 5-min intervals and record the time as well as mushroom mass and dimensions. Repeat this process to obtain data over 45 min.

RESULTS

As the mushroom pieces incubate in the salt solutions, their mass decreases over time (Fig. 4). We observed two regimes: during the initial 5 min, there was a rapid increase in mush-

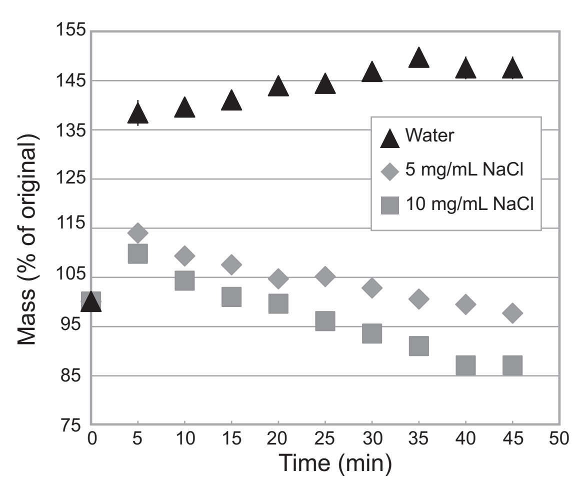

Fig. 4. Mass of mushroom pieces as a function of time. The plot shows mushroom mass as a percentage of its original mass as a function of time incubated in NaCl solutions. Values represent the average of three independent mushroom pieces for each salt concentration. Error bars show SDs; where not visible, they are smaller than the symbol size.

room mass. In contrast, at time points after 5 min, we observed that there was a steady reduction in mushroom mass over the experimental timescale. We estimated that the initial, rapid increase of mass is primarily due to the influx of water into the mushroom, which has a significant air content. Subsequently, the concentration gradient of salt drives water out of the mushroom. To simplify our use of Fick's first law to calculate the diffusion coefficient of water, we focused on the linear regime: students determine the slope of the data acquired between 5 and 45 min by performing a linear fit.

Other essential parameters, as described by Fick's law, include the surface area of each mushroom piece, the salt concentration of the solution, and the salt content of the mushroom. The mineral content of white button mushrooms can be easily obtained from the literature (17). Together with the students' observed results, they can apply Fick's law to calculate the diffusion coefficient of water; students typically obtain diffusion coefficient of water value of $\sim 10^{-3}$ cm^2/s (average of $n = 16$ students). This diffusion coefficient of water value may seem surprisingly large, given the self-diffusion coefficient of water at room temperature, $\sim 10^{-5}$ cm^2/s. However, with careful consideration of the observed buoyancy of mushrooms, this measured diffusion coefficient of water makes sense: the self-diffusion coefficient of water is typically ~10,000 times smaller than the diffusion coefficient of water in air at equivalent temperature ($\sim 10^{-1}$ cm^2/s) (6). Given that the density of a mushroom is 0.41 g/cm^3 (18) and a large fraction of the mushroom is air, the measured value of diffusion coefficient of water value of $\sim 10^{-3}$ cm^2/s is reasonable.

DISCUSSION

In this article, we present three simple examples of diffusion in food and cooking that connect Fick's first law to real-life phenomena. Since only simple algebra is required, these exercises can be targeted to undergraduate freshmen students, including nonscience majors, for whom diffusion is an important concept that can be challenging to grasp. These lessons also provide a foundation for more sophisticated analyses of diffusion, such as using Fick's second law and second-order partial differential equations.

To demonstrate how this laboratory exercise relates to food and cooking, we discuss in class how the concept of diffusion relates to practical examples in cooking such as brining a turkey or marinating tofu. Related problems are presented in homework assignments and on exams. We also provide students with a postexperiment recipe [marinated tofu wraps with salt-pickled mushrooms (see APPENDIX 3: POSTEXPERIMENT RECIPE)]. While this recipe is not mandatory, some students are curious to explore culinary applications of their salt-pickled mushrooms and complete each recipe at home.

Conclusions

In addition to mastering the scientific concept of Fick′s law, these hands-on activities encourage students to practice the scientific method and to think like scientists. For example, our simple experiment to determine the diffusion coefficient of water by salting mushrooms provides an opportunity for students to perform experiments and analyze data in a classroom setting. The experiments are easy to execute and require little preparation on the part of the instructor or laboratory assistants. The protocol can also easily be extended to incorporate tools and methods for analysis in quantitative biology and biophysics; image analysis and data fitting, for example, are essential in scientific research.

We have observed that students benefit from this experience in scientific experimentation as they progress through the course: subsequent laboratory activities also require students to perform experiments, collect, and analyze data, for example, to determine the elastic modulus of gels. In addition to their weekly laboratory exercises, students conduct a final project in the last 4 wk of the course where they are challenged to investigate the science behind a pie. Here, the students are required to design experiments to investigate the science of pie, such as the role of fat composition on crust flakiness or baking temperature on crust color and texture. In addition, many students apply their knowledge of diffusion. For example, students have chosen to investigate the time required to marinade chunks of apples or to bake pies of different geometries; this ability to apply their knowledge of diffusion and experimental design suggests that the students benefit from these simple exercises on the principles of diffusion. Engaging students in scientific research is an essential aspect of science education that can be challenging to achieve in a classroom setting; active learning is an effective pedagogical technique (10).

APPENDIX 1: SPHERIFICATION RECIPE

Ingredients

- 2 liters water
- 20 g calcium chloride
- 200 ml of your favorite flavored liquid
- 1 g sodium alginate

Directions

1. Whisk together the calcium chloride and water to achieve a final concentration of 1% (wt/vol).

2. In another bowl, blend together the sodium alginate and your favorite flavored liquid with an immersion blender; this will yield a 0.5% (wt/vol) solution. Let this solution sit for 30 min to eliminate air bubbles.

3. Using a spoon or liquid dropper, carefully place the flavored liquid into the calcium chloride bath. Depending on the desired thickness of your alginate skin, keep the drop in the bath for 30 s to 5 min.

4. Remove your sphere with a slotted spoon to drain excess calcium chloride solution.

5. Enjoy immediately!

APPENDIX 2: PROCEDURES FOR CALCULATING THE DIFFUSION COEFFICIENT IN A MUSHROOM-SALT WATER SYSTEM

This experiment can be done independently or in small groups. The activity can easily be modified to convey the creative process of experimentation in science by having the students choose the parameter they vary in the experiment, such as surface area or salt concentration.

Procedures

1. Prepare two salt water solutions of 5 g NaCl/100 g water and 8 g NaCl/100 g water in small jars, mugs, or cups. Swirl the solutions to dissolve the salt.

2. Stem and peel the caps of the mushrooms, ensuring that the skin is removed as well as any brown fins on the bottom side of the mushroom caps. Record the initial mass of the mushroom pieces.

3. Place mushroom pieces in the salt-water solutions; a spoon, fork, or weight may be required to keep the mushrooms submerged in the water. Use at least one mushroom piece per solution.

4. Remove the mushroom pieces at 15-min intervals. Dab them dry on a paper towel, and record the time and mushroom mass, and measure the dimensions of the mushroom pieces or take a picture.

5. Put the mushrooms back in the salt-water solutions and repeat over 3 h.

6. To determine mushroom surface area, record the mushroom dimensions: acquire images of the mushroom pieces and use quantitative image analysis. An image of a ruler or a coin taken at the same position as images of the mushroom pieces facilitates calibration.

Procedures for Data Analysis

1. Prepare a spreadsheet and enter your data into columns for time and mass for each mushroom piece you measured. Be sure to record the concentration of salt solutions and the smallest dimension of each mushroom piece.

2. Plot mass versus time for each mushroom piece.

Followup Questions

1. Determine the slope ($t = 5 \rightarrow 45$ min) of mass versus time data for each salt-water solution. Consider how the slope relates to your macroscopic observations for each salt concentration. How does the gradient of salt (driving force) result in the flux (response)?

2. To determine a value for D, calculate the following relevant parameters:

A. Flux of water (J)
B. Concentration of salt solutions (molarity or in mol/l)
C. Smallest dimensions of each mushroom piece (dx, length scale)

3. What value of D do you obtain? How does this compare with what you expected? Explain.

4. Given that the diffusion constant of many molecules is ~10,000 times faster in gas compared with liquid, what does this tell you about the composition of the mushroom? Explain in the context of any other empirical data you have collected.

5. Explain how the initial rate of mass transport (0–5 min) of your plot changes over time. Describe what is happening at longer timescales (5–45 min): why does the rate of mass loss slow down?

6. This simplified framework for understanding the complex process of mushroom pickling includes many assumptions. Describe how you would develop a more complete theoretical description of your mushroom experiment.

APPENDIX 3: POSTEXPERIMENT RECIPE

This is a recipe for marinated tofu wraps with salt-pickled mushrooms.

Ingredients

- 150 g fresh tofu, firm
- Fresh herbs
- Rice paper
- Salt-pickled mushrooms

Salt-pickled mushrooms. The salt-pickled mushrooms require the following ingredients:

- Salt water marinade: 5 g salt in 100 g water
- White button mushrooms, peeled and sliced into ~0.5-cm-thick slices

Marinade. The marinade requires the following ingedients:

- 3 Tbsp. soy sauce
- 1 Tbsp. sesame oil
- 1 Tbsp. canola oil
- 1 Tbsp. freshly grated ginger

Dipping sauce. The dipping sauce requires the following ingredients:

- 1 tsp. chili oil
- 2 tsp. sesame seeds
- 1 Tbsp. sesame oil
- 1 Tbsp. rice vinegar
- 1 tsp. honey

Directions

1. Prepare the salt-water solution for your mushrooms. Prepare the mushrooms and then place them in the salt solution. Set this preparation aside for 45–60 min.

2. In a nonreactive dish, such as a glass bowl, toss together the marinade ingredients with the tofu.

3. Marinate this for 30 min in refrigerator.

4. Drain off the marinade.

5. Retrieve the mushrooms and mince them into tiny pieces.

6. Prepare the dipping sauce by mixing together all ingredients in a small bowl.

7. Prepare the rice paper wraps by running them under hot water. Set them on a plate to rest for a few minutes until they become soft and hydrated.

8. To serve, place tofu and green herbs in the rice paper wraps. Garnish the wraps with salt-pickled mushrooms. Roll the wraps and dip them in dipping sauce. Enjoy!

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: L.Z., K.N., and A.C.R. performed experiments; L.Z. and A.C.R. analyzed data; L.Z. and A.C.R. interpreted results of experiments; L.Z., K.N., and A.C.R. prepared figures; L.Z. and A.C.R. drafted manuscript; L.Z., K.N., and A.C.R. edited and revised manuscript; L.Z., K.N., and A.C.R. approved final version of manuscript; A.C.R. conception and design of research.

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