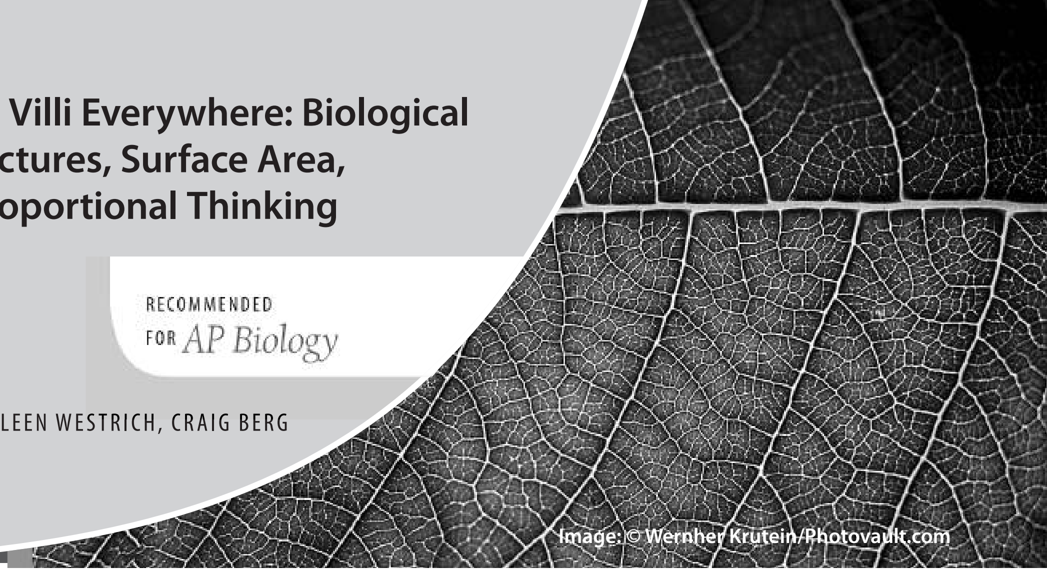
INQUIRY & INVESTIGATION

Villi, Villi Everywhere: Biological Structures, Surface Area, & Proportional Thinking



RECOMMENDED FOR *AP Biology*

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Abstract

We present an activity that models the teaching of content knowledge that transfers to many areas of the life sciences and simultaneously targets growth in cognitive development. The activity provides students with concrete objects and thinking experiences that facilitate an understanding of how surface area, in the context of biological systems, is a critical and common factor in life-supporting functions. Alveolus structure and gas exchange in the lungs, nephron structure and water retention in the kidneys, villus structure and nutrient absorption in the small intestine, and root-hair structure and nutrient absorption in plants are all biological examples in which surface area plays a key role in living things. In addition, this activity incorporates components that engage students in thinking about proportional reasoning, as many students lack the proportional thinking skills needed to fully understand this structure/function relationship or to transfer the relationship to a new, but related, situation.

Key Words: *Structure and function; surface area; models; cognitive development.*

What do the intestines, kidneys, lungs, leaves, and roots all have in common? Part of the answer pertains to how surface area plays a role in maintaining the life functions of plants and animals. The other part of the answer is embedded in the old math joke, "Do you know that five out of four people have trouble with fractions?" This joke, and the number of chuckles versus puzzled looks produced, parallels what research reveals about a learner's thinking, and matches what classroom teachers see everyday. That is, many people (children and adults) struggle with proportional reasoning. They have difficulty with ratios, fractions, graphing, data analysis, gambling, and concepts in science and math that are partially rooted in proportional reasoning. This article presents an activity that is designed (1) to stimulate and foster proportional thinking and (2) to facilitate understanding of how surface area, in the context of biological systems, is a critical and common factor in life-supporting functions.

Surface area is a critical and common factor in life-supporting systems.

○ Science Content & Proportional Reasoning

If learners (young or old) came to school with a fully developed set of thinking abilities they could use to cognitively wrestle with any science content put in front of them, teaching simple and complex science content would be easy at any level of schooling. Of course, such is not the case. While educators readily accept a learner's uniqueness in the form of generic labels such as LD, ED, ADD, or ADH, and know the importance of lesson adaptations that will give students with special needs an opportunity to learn, nonlabeled learners are treated as typical and homogeneous, as if they have full and similar sets of mental tools needed to grasp particular science content. The complexities of the science can be mentally demanding, and success in the science classroom may be more dependent on the limiting factor of differentiated student cognitive development and the mental tool set available to the learner than on other factors. While there are many other examples, one such limiting factor, an important part of any learner's mental tool set, is proportional reasoning.

Proportional reasoning has long been described as one indicator of, and one of the thinking abilities that constitute, the highest level of cognitive development – formal operational thought. Science and math teachers routinely deal with the presence or absence of proportional thinking when using ratios, data sets, and formulas that have direct or inverse relationships. Hoffer and Hoffer (1992) concluded that algebra, geometry, chemistry, physics, and aspects of biology are difficult to learn without the presence of proportional reasoning. The *National Science Education Standards* (National Research Council, 1996) include numerous references to thinking and reasoning skills as integral components of doing and learning science.

The learner is at an advantage or is handicapped by the presence or absence of proportional reasoning. Students both young and old struggle with this higher-level thinking ability while trying to comprehend concepts in science and math. Adey (1999) found that only 30% of 16-year-olds indicated the developed ability to think proportionally, while Bybee and Sund (1990) showed a distribution of 13.2% formal operational thinkers by 9th grade, increasing to 49.5% formal operational thinkers by 12th grade. Similar results were reported by Wavering (1985), Berg and Phillips (1994), and Slattery (2009). "The acquisition of proportional thinking skills in the population at large has been

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unsatisfactory. Not only do these skills emerge more slowly than originally suggested, but there is evidence that a large segment of our society never acquires them at all" (Hoffer, 1988: p. 285). It appears that few students have this particular mental tool to aid their understanding when studying science concepts that involve proportional thinking, and this factor has not changed over the past 30 years. To become better informed as to what mental tools students are bringing to classrooms, D. G. Phillips (2010) has created an assessment that provides indicators of students' proportional reasoning abilities.

What can classroom teachers do to help students improve their proportional reasoning? Science teachers have options when designing lessons and accomplishing content objectives. Students can be placed in situations that will present opportunities to engage in proportional reasoning, while simultaneously targeting and accomplishing content objectives. Attending to proportional reasoning can be a purposeful part of this process, and development of this important reasoning skill should not be left to chance. Activities and questioning designed to stimulate thinking with regard to proportional relationships are key. The focus of this article and lab is on helping students to make connections between surface area and structures that perform vital life functions in plants, animals, and other organisms, while giving them opportunities to mentally wrestle with proportional reasoning skills.

○ Science Content, Proportional Reasoning, & Classroom Instruction

How does proportional reasoning connect directly to the lungs, kidneys, intestines, cells, and plant roots? The answer lies in examples such as the relationships between villus structure and nutrient absorption in the small intestine (Figure 1), nephron structure and water retention in the kidneys (Figure 2), alveolus structure and gas exchange in the lungs (Figure 3), root-hair structure and nutrient absorption in plants, leaf ventation and nutrient transport (Figure 4), and any other function in which surface area is key to life support. With regard to all of these examples, the given structure dramatically and proportionally increases the amount of surface area – critical for accomplishing the physiological activity that supports life function. Proportionally, a decrease or increase in surface area has corresponding negative or positive results, some of which can be life-threatening. The efficiency of these structures is increased dramatically and proportionally by irregular surfaces with dips, bumps, or projections that branch into smaller pathways or alter the ratio of x to y. Plant root systems branch smaller and smaller into numerous tiny hairs; if there were fewer but larger roots, how would total surface area and the capacity to absorb nutrients be altered? Tree canopies also exhibit branching pathways from the trunk to branching tips; what if trees had bigger leaves, but half as many? How would total leaf surface area and the resulting capacity for photosynthesis be affected? If red blood cells were saucer-shaped or spherical instead of bi-concave (Figure 5), how would their total surface area affect their capacity for oxygen/carbon dioxide exchange?

An examination of the role of the alveoli in the lungs will serve as an example. Their function is gas exchange. They absorb freshly inhaled oxygen into the bloodstream via tiny capillaries near the wall of the alveolus and release the cellular respiration waste product, carbon dioxide, into the atmosphere during exhalation. Heavy smokers damage their lungs, decreasing functional alveoli and surface area, limiting the exchange of oxygen and carbon dioxide. The reduction in the number of functioning alveoli proportionally changes the amount of surface area available for gas exchange, which affects the physiological function in an obviously negative way.

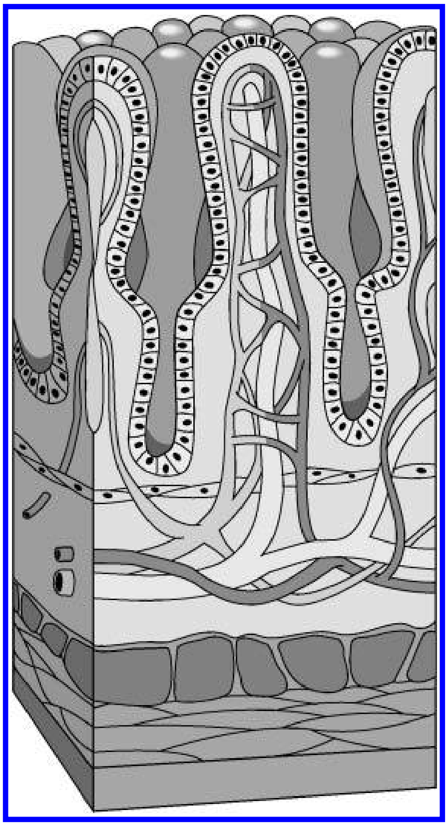

Figure 1. Intestinal villi and nutrient absorption. (Image by Lifeart © 2010 – Wollers, Kluwer, Health Inc. Lippincott, Williams and Wilkins – All Rights.)

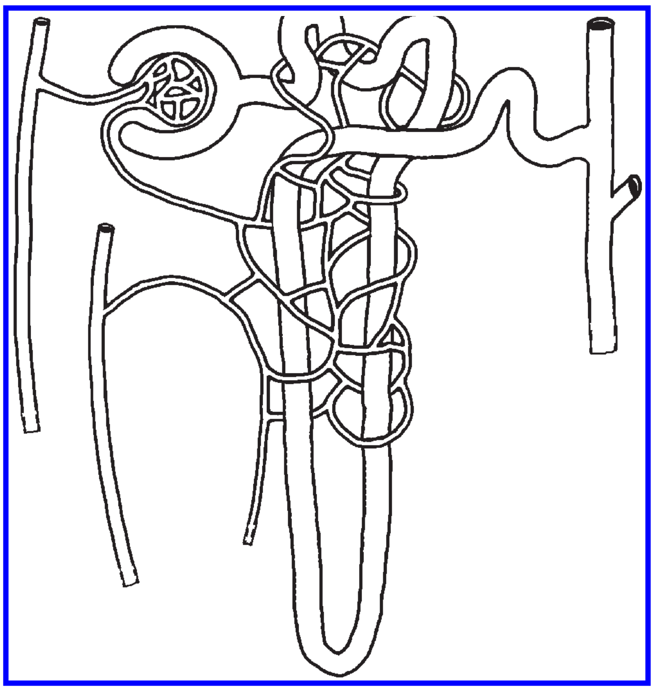

Figure 2. Nephron in kidneys and filtration of waste products. (Image – www.medical –illustrations.ca.)

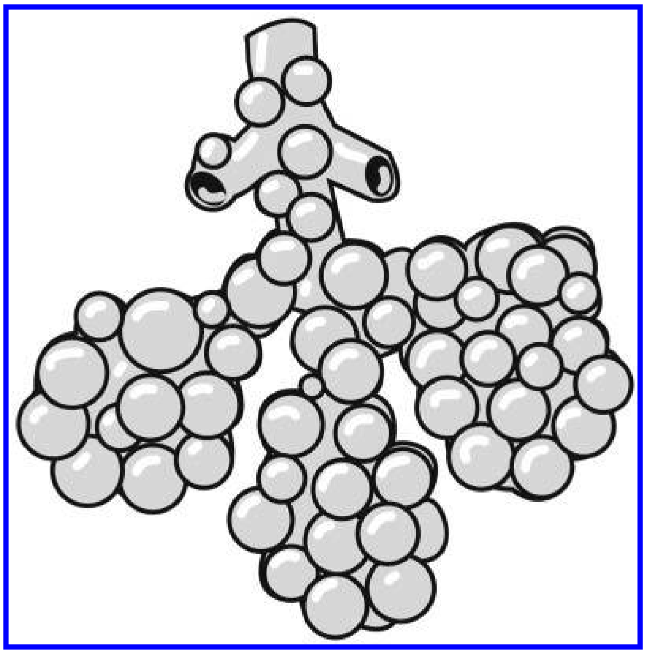

Figure 3. Alveoli in lungs and gas exchange. (Image by Lifeart © 2010 – Wollers, Kluwer, Health Inc. Lippincott, Williams and Wilkins – All Rights Reserved.)

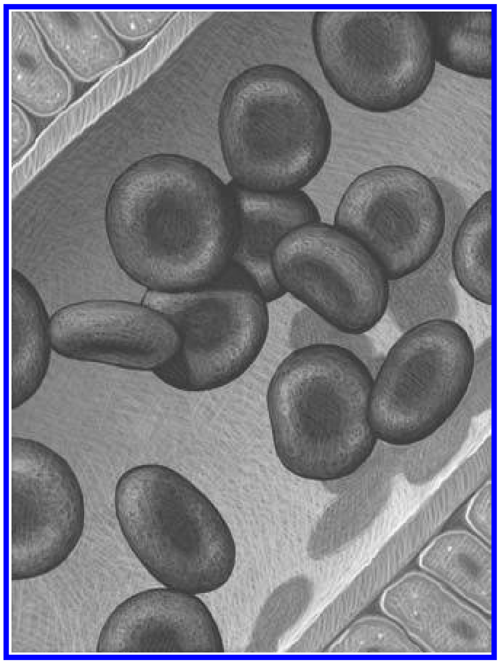

Figure 5. Surface area effects on diffusion rate such as biconcave red blood cells. (Image by Lifeart © 2010 – Wollers, Kluwer, Health Inc. Lippincott, Williams and Wilkins – All Rights Reserved.)

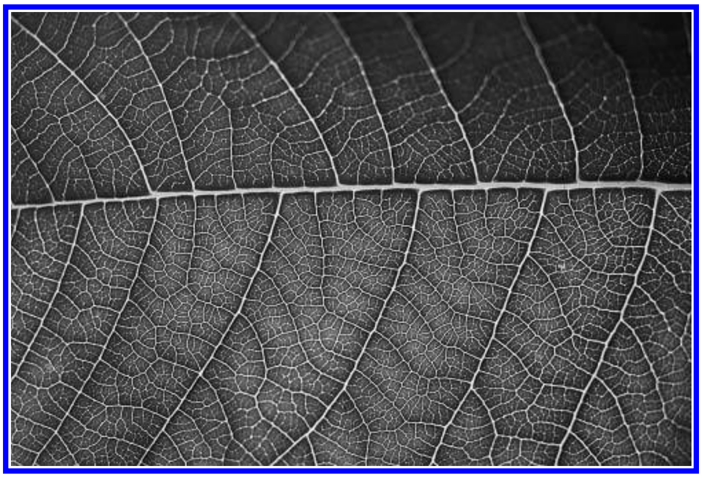

Figure 4. Branching veins on a leaf and nutrient transport. (Image by Wernher Krutein / Photovault.com.)

What if the alveoli were shaped differently? What would happen to surface area if these balloon-like air sacs were smaller in size, or rod-shaped? If alveolus diameter were reduced by half, how much diffusion could occur? What if the lungs had no alveoli at all but were simply two big balloons, with gas exchange occurring at the walls of the balloons? Without each lung having thousands of tiny balloons at the end of each branching pathway, how much surface area would be available for diffusion of gases?

The same proportional relationship – the physiological capacity corresponding to available surface area – can be examined when looking at the absorption of nutrients in the villi of the small intestines, the retention of water by the nephrons, the delivery of oxygen by red blood cells in the circulatory system, the absorption of nutrients in the roots of plants, and the photosynthetic capacity of leaves. Figures 1–5 depict some of these structures and functions that are affected by proportional relationships.

○ Surface Area – the Commonality

The key concept highlighted in the alveolus example is that the amount of surface area affects the capacity of the lung tissue to function; the quantity of bumps, projections, and branching pathways is proportional to the structures' capacity to function and, thus, sustain life. Students often miss this form/function connection, in part because they lack proportional thinking. When addressing this deficit, it helps to provide students with a concrete, visual activity that highlights the essence of how surface area is integral to the physiological functions. The activity presented here, "Villi, Villi, Everywhere," is designed to address the concept of surface area and to give students an opportunity to develop proportional reasoning. The activity begins in a visual, kinesthetic, and conceptual manner, then proceeds with calculations to show quantitative comparisons, and, lastly, incorporates mental-abstraction questions. These questions are designed to have students mentally wrestle with ratios and proportions of x to y, and interpolate or extrapolate beyond the directly observable. This activity can be tailored to the life sciences in middle school and to regular or advanced biology in high school – the evidence indicates that even high-level biology students struggle with this concept. The authors include this activity within the digestion unit when studying the human body. While this activity focuses on the structure of villi in the small intestines, similar activities would work equally well when investigating alveoli, nephrons, or root systems. See the lab Activity Sheet for potential extensions of the concept to structures of alveoli and nephrons.

○ Endpoints

In order to be consistent with the *National Science Education Standards* and state science standards, lessons and teacher–student interactions should target many goals for the students, including problem solving, thinking skills, and development of a functional, transportable understanding of science content. All too often, science content goals are the sole target, while growth in thinking is sidelined. The "Villi, Villi

ACTIVITY SHEET
Villi, Villi, Everywhere

Teacher Notes 1: Getting Students Started

1. Give students the activity sheet #1 and make sure they respond to the their prediction question before moving on to build the model.
2. Give the students the materials needed (non-latex rubber gloves, twist ties, tape, index cards and rulers, student sheet #1 labeled "Villi, Villi, Everywhere," and save student activity sheet no. 2 labeled "Tips" for later). Students will construct something that looks like Figure 6.

Teacher Notes 2: Post-Model-Building Questions

1. When students have completed both Part A and Part B, bring the students together in a large group. Make a data table with the X column labeled "number of villi" and the Y column labeled "total surface area." Record how many villi they put on their card, and the corresponding total surface area (in square centimeters) for their villi model.
2. Ask the small groups to examine the numbers for data that look out of place. Were the calculations incorrect, or are the numbers accurate? If the numbers look erroneous, ask the small group to pose questions to the group(s) responsible for the erroneous numbers, for the purpose of understanding how the surface area was calculated. Then react to the small group's methodology in terms of reliable methods.
3. Ask "What is the average gain in surface area per villus?"
4. Give the students graphing paper or graphing boards and ask them to construct a graph using the data table. So that students can compare graphs with each other, standardize their graphs by suggesting that on the X axis they put 0–10, representing number of villi (fingers) on the card; and on the Y axis 0–30, representing amount of surface area.
5. Ask "What have we learned from developing a graph of the data?"
6. Ask the small groups to use the graph to estimate how much surface area would exist for somewhere in between two data points. "Since no group had (pick a number of villi that no group used) villi, how much surface area would you expect to find?"
7. Ask students to use the graph and existing data points in order to extrapolate the maximum gain in surface area if villi covered the card completely.
8. Ask students to write a statement that summarizes the nutrient absorption benefits due to the villi.

Figure 6. Photo of model villi.

Student Activity Sheet no. 1: "Villi, Villi, Everywhere"

Building & Calculating

The digestive and excretory system is one long, open tube from mouth to anus. Food is not really "inside" your body until the nutrients enter your bloodstream. The bloodstream is responsible for delivering the nutrients to all the cells of the body, which need them for energy. The absorption of nutrients occurs in the small intestine, which has structures that allow for the maximum amount of absorption. The small intestine is lined with millions of tiny, finger-like projections called villi. The wall of each villus is one one cell thick; nutrients pass through it and into the blood vessels on the other side.

Why is the structure of villi so useful for absorbing the maximum amount of nutrients?

The answer to this question has to do with surface area. The surface area of the small intestine is greatly increased by the tiny finger-like projections. Look at Figure 6, which shows a 2 × 4 cm flat area with 7 villi projecting from the surface. Predict how much surface area there is in Figure 6 with the villi versus just the flat surface – take this prediction, along with a short explanation, to your teacher and then do the following.

Part A. Your job is to create a model explaining the meaning of surface area and how it can affect the amount of nutrients absorbed.

1. Calculate the area of a flat surface. Use an index card – roughly 8 cm × 12 cm. What is the surface area?
2. Find the surface area of one villus.
   a. Use the "fingers" on vinyl gloves to represent the villi of the intestine.
   b. Cut one finger and put your "villus" onto the flat surface of the index card (see Figure 7).
   c. Measure the surface area of one "villus." Remove the villus and set it aside.
3. Using multiple "fingers" and twist-ties, create a model representing a surface covered with many villi, using the index card from part 1 (see Figure 6). Tape the twist-tie down to the card to support the finger so that it stands up.

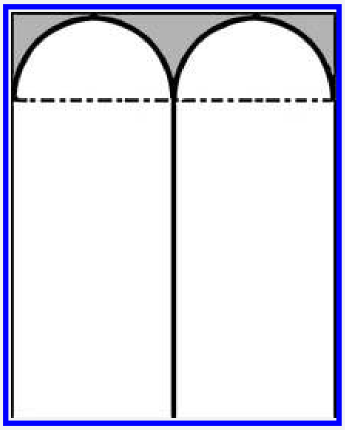

Figure 7. Rubber glove finger (cut and laid flat) to measure surface area of one villus.

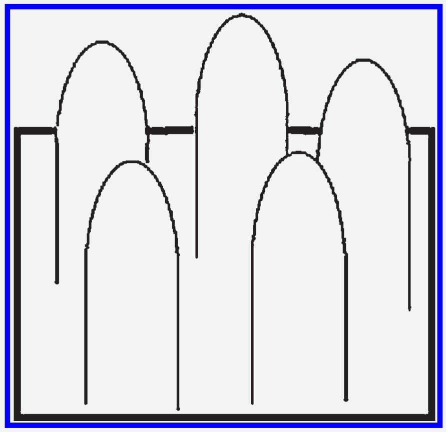

Figure 8. Model with many villi.

a. Calculate the surface area of all the villi on the card, and compare this measurement with the surface area of the flat surface (without the villi).

Part B. You must answer the following questions:

1. What is meant by the "surface area" of something?
2. How did you measure the surface area?
3. What is the surface area of your surface without the villi?
4. What is the surface area of your surface with the villi?
5. What is absorption?
6. Discuss and explain the difference and relationship between the structure and function of the intestinal villi.
7. How does surface area affect the amount of molecules that can be absorbed?

Student Activity Sheet no. 2 – Tips Optional

Calculating Square Millimeters of One Villus Surface-Absorption Area (Figure 7)

Simple –	L × W = Square mm of whole rectangle (includes gray area)
Accurate –	L × W of rectangle = Square mm of rectangular part of the glove (includes the dotted-line boundary downward)
	plus
	$\pi *r^2$ = Square mm of circle = area of circular piece of the finger (this calculation excludes the gray area)

Calculating Total Square Millimeters of Villus Surface-Absorption Area on the Whole Card (Figures 7 & 8)

Total Surface Area of Villi on Card = Square mm of one villus × number of villus on the card

Lab Extensions & Challenges

1. *Surface Area of Alveolus*: The alveolus is basically a sphere, and while students could use the Internet to quickly find a formula for surface area of a sphere, challenge them to figure out a way to obtain an estimate using a physical model. Similar to the villi lab, when students cut apart the rubber finger and laid it flat and then calculated the area of the rectangle and circle, can your students figure out how to do this with a sphere? One solution is to blow up a balloon, papier-mache the balloon, let it dry, and then cut up the papier-mache surface area into squares until they can approximate the surface area. Graphing the results from a number of balloons of different sizes produces an interesting graph and shows a relationship between diameter of the balloon and surface area. Or students can use the formula $4*p*r^2$, plug in some different radius numbers, then graph the results and look at the relationship.
2. *Surface Area of Nephrons*: Diagrams of a nephron showing the many branching pathways of capillaries that weave around the tubule. There is also a long segment of capillary that is packed into the spherically shaped glomerulus. Both of these structural components aid in waste product leaving the capillaries and being collected by the tubules for release from the kidneys to the bladder. Surface area of a tube or cylinder (without the endcaps) can be calculated by $2*\pi*r*h$, and volume of a tube can be calculated by $p*r^2*h$. Challenge students to use what they learned in the villi activity to answer the question, "What is it about the structure of a nephron that contributes to the most efficient function of waste product leaving the capillaries and crossing into the tubules?"

Everywhere" activity demonstrates that science teachers can target the important goals of science content by developing a solid notion of surface area that translates to many other aspects of biology and physiology. At the same time, the activity stimulates and develops thinking tools that students need in order to understand concepts in science and math. Many students need the concrete, hands-on, minds-on, and three-dimensional, visual nature of the activity. When given a proper chance, students can build a more robust understanding of the science content and further develop the reasoning and thinking abilities that are so critical to learning and living.

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