Validating The Core Concept Of “Mass Balance”

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Abstract

We have created a conceptual framework for the core concept of “mass balance.” Unlike the previous conceptual frameworks that we have created and validated, the framework for “mass balance” is simply a description in words of the fundamental mass balance equation and the implications of the equation. We surveyed physiology faculty and asked them to rate the importance of “mass balance” as defined by the conceptual framework and also to rate the importance for their students of being able to apply the core concept to liquids, gases, solutes, and solids. Respondents indicated that “mass balance” is important and that our conceptual framework provides a useful tool for teaching and learning. We discuss several examples of how “mass balance” can be used in making sense about a variety of physiological phenomena.

INTRODUCTION

In 2000, Modell (1) identified conservation of mass (“mass balance”) as one of seven general models that can help students understand many physiological phenomena. In 2009 a group of physiology education researchers identified a set of “core principles” of physiology (2); “mass balance” appeared on this list. The physiology teaching community was later surveyed to determined what the core concepts of physiology were (3). The resulting list was very similar to the 2009 list, and respondents again identified “mass balance” as a core concept.

In their reconsideration of the core concepts, Michael and McFarland (4) defined the core concept of “mass balance” with the following words:

“DEFINITION of Core Concept of Mass Balance: The contents of any system, or compartment in a system, is determined by the inputs to and the outputs from that system or compartment. This is a simple general model that applies to all physical systems.

ELABORATION of Core Concept of Mass Balance: Mass (or matter) can be liquid (e.g., water, blood), gas (e.g., oxygen, carbon dioxide), solute within a liquid medium (e.g., ions, glucose, hormones), or solid (e.g., CaPO4 in bone). The region of interest may be considered to be a compartment with, potentially, multiple entry and exit paths. The quantity of mass within a compartment depends on the initial quantity of mass in the compartment, the rate of entry of mass into the compartment, and the rate of exit of mass from the compartment.”

To make the core concepts more useful as tools for teaching and learning physiology, we have written (“unpacked”) and validated conceptual frameworks for four of the core concepts: “flow down gradients” (3), “homeostasis” (5), “cell membrane” (6), and “cell-cell communication” (7). Each of these conceptual frameworks is a hierarchically organized statement of the component ideas that make up a particular core concept (8).

In this paper, we present our conceptual framework for “mass balance” and the results of polling the physiology teaching community about the validity and utility of this framework. We also discuss some examples of how “mass balance” can be used to make sense of physiological phenomena.

THE CONCEPTUAL FRAMEWORK FOR “MASS BALANCE”

Our thinking about this core concept began with the recognition that “mass balance” can be represented by a simple equation (where X represents some real or virtual body compartment):

\[ \text{Mass}_X = \text{Mass}_{X,\text{initial}} + \text{Mass}_{X,\text{in}} - \text{Mass}_{X,\text{out}} \]

The “flow down gradient” core concept (3) is similar in that it too can be represented by a simple equation. Both of these core concepts belong to a group of core concepts that are universally applicable in the physical world, inanimate and animate (4). As such, these core concepts can be unpacked in a variety of ways to meet the needs of those who will be using them. Thus our efforts to unpack “mass balance” drew on our understanding of the ways in which
this core concept is used by teachers and students in making sense of physiological phenomena.

There are, of course, some additional ideas that constitute parts of the “mass balance” core concept. An obvious one is the definition of a compartment (Table 1). A compartment may be an actual space defined by anatomical boundaries (e.g., the alveolar gas space) or a virtual space defined by conceptual boundaries (e.g., a portion of a blood vessel or capillary bed). We also realized that this concept is used in understanding four different kinds of “mass” and that each requires a slightly different formulation of the basic equation.

The conceptual framework that describes the core concept of “mass balance” can be seen in Table 1. This is the framework that was to be validated in our survey (see below). However, before using the core concept of “mass balance” to make sense of the various physiological phenomena to which it is applicable, students must understand an additional set of ideas about how to apply the concept to the four forms of matter mentioned. We have added these ideas to the conceptual framework in Table 2.

**VALIDATING THE CONCEPTUAL FRAMEWORK FOR “MASS BALANCE”**

As discussed above, the first core concept that we unpacked, “flow down gradients” (3), is a member of the class of core concepts that is universally applicable in the physical world (4). The next three core concepts we unpacked, “homeostasis” (5), “cell-cell communication” (7), and “cell membrane” (6), are core concepts that are only applicable in the biological (animate) realm (4). They unpack in a way that is quite different from that seen in the conceptual framework for flow.

In previous projects to validate core concepts, we asked respondents how important it was that their students understood each statement in the framework. However, the framework (Table 1) for “mass balance” is simply a verbal description of the mass balance equation and the different conditions under which it might be applied. Assessing the importance of each statement did not seem useful to us. Either the core concept was important for student understanding of physiology or it was not.

On the other hand, the addendum to the conceptual framework (Table 2) describing the application of the concept of “mass balance” to different forms of matter that move in the body can be assessed one statement at a time.

The survey that we used thus asked participants to respond on a Likert scale to six questions about our proposed framework (see Table 3).

We also asked where respondents taught, what level of students they taught, and whether they were currently using a core concepts approach in their teaching.

Surveys were prepared and distributed using Google Forms and SurveyMonkey. Invitations to participate in the survey were sent to individuals from email lists from several previous surveys.

**RESULTS**

Thirty-three individuals responded to our invitation to take the survey. Table 4 tabulates the kinds of educational institutions at which respondents teach. Respondents were at institutions distributed across the United States, in Canada, and in Australia. Twenty-nine of the respondents teach undergraduate students, three teach professional students, and one teaches graduate students. It is possible that some respondents teach more than one population of students, but we did not ask about this. Twenty-six of the respondents said they were using core concepts in their teaching, six said they were planning to, and one indicated he or she was not using them.

The responses we received support our belief that the core concept of “mass balance” is an important one for students to understand and be able to apply. Thirty of the 33 respondents gave “mass balance” (Question 6) a rating of 5, 4, or 3;...
no one rated it as 1 (Unimportant). The average of these ratings, generally regarded (9) as a valid approach to determine the relative importance of Likert scale responses, is 4.03 (see Table 5). However, the responses also show that the respondents seem to regard students’ ability to apply “mass balance” to liquids, gas, and solute as perhaps more important than student understanding of the underlying core concept (Q8-10). Applying “mass balance” to solids (Q11) is seen as somewhat less important.

Interpreting the written comments about the “mass balance” conceptual framework (Table 6) is more difficult, and certainly more subjective, than analyzing the results of the Likert scale questions. Seventeen of the 28 written responses either indicated satisfaction with the conceptual framework or simply offered comments on the difficulty of the concept. There were 11 suggestions for additions to the framework or significant changes to it. The examples seen in Table 6 reinforce our belief (4) that none of the conceptual frameworks are to be regarded as the final word. Rather, physiology teachers may want to edit or change them in ways that they believe will best serve their students.

**DISCUSSION**

The results of our survey of physiology faculty support our belief that we have correctly described the core concept of “mass balance” and that this core concept (and its extensions) are viewed as useful tools for teaching and learning. It is particularly interesting that our respondents see the concrete applications of the core concepts to liquids, gases, and solutes as slightly more important than the abstract core concept itself. Whether this reflects the pedagogy that these faculty employ in helping their students apply this core concept is not revealed by our survey.

The value of using a core concepts approach to help students make sense of physiological mechanisms derives from the fact that core concepts provide a tool for building robust mental models that have a broad range of applicability (4, 8). The core concepts that we have identified fall into a number of categories (4) including those that are applicable to only living systems (e.g., “homeostasis,” “cell-cell communication,” and “cell membrane”) and those that are applicable to all physical systems (e.g., “flow down gradients” and “mass balance”). Some students may find the core concepts that apply to all physical systems more easily understood because they have seen examples of them all of their lives. For instance, “mass balance” can be viewed as describing a simple reservoir system (e.g., a bathtub) with multiple inlets and outlets (1).

This familiarity with the “mass balance” core concept may help students make sense of physiology since this core concept forms the basis for discussions dealing with respiratory, cardiovascular, and renal topics in essentially all physiology textbooks. These discussions use various forms of the applications of mass balance outlined in Table 2 to determine the variable of interest. In all of these discussions, the system in question is assumed to be in a steady state, so the volume of the compartment (reservoir), and the content of mass within the compartment, remain constant.

In respiratory physiology, variables of interest include the mass (fraction or partial pressure of oxygen or carbon dioxide) in the alveolar compartment. In the cardiovascular system, the variables include the blood flow rate through the systemic vasculature (cardiac output), the volume of oxygen (mass) leaving the vascular compartment and entering the tissues (oxygen consumption), and the volume of carbon dioxide (mass) leaving the tissues and entering the vascular compartment (carbon dioxide production). The renal system discussion applies the core concept to the nephron to determine the rate of solute reabsorption, the rate of solute secretion, and the volume of plasma that has been “cleared” of solute.
that contribute to various phenomena in the cardiovascular system. Thus the pressure in a vessel depends on the vessel volume and recoil of the vessel wall.

Exercises have been presented to help students utilize these mental model building tools to examine the cardiac cycle and the factors determining the arterial pressure pulse (1, 10). In the latter case, students are encouraged to imagine that they are “standing” in the arterial tree (i.e., the “reservoir”) and observe the changes that occur in the reservoir volume and pressure during systole and diastole. By plotting the changes that they see as function of time, and by repeating the exercise with varying systolic and diastolic times, varying arteriolar resistance, and varying vascular recoil (1/ compliance), they can build a mental model that allows them to predict how the arterial pressure pulse will change under a wide variety of conditions.

Thus far the examples that we have provided have focused on “mass balance” as defined in Table 1. However, the framework can be extended to also apply to heat balance. The amount of heat in a system depends on the initial heat content, the flow of heat into the system, and the flow of heat out of the system. Thus, students may use this core concept in their study of temperature regulation.

If students are to utilize the core concept of “mass balance” in their efforts to make sense of physiology, it is essential that physiology teachers explicitly and consistently model the use of this concept to explain phenomena and solve problems and that they ask their students to do the

There are a number of reasons why many students fail to recognize that the equations presented in these discussions are fundamentally the same: (3) the symbols used look very different, (4) the textbook does not help them make connections between the current and previous discussions. As a result, many students simply memorize the equations without recognizing the concepts that each describes. If instead, students use the “mass balance” core concept (the reservoir model) as an organizing framework, the task of making sense of these equations would be greatly simplified.

The above examples illustrate applying the “mass balance” core concept to models of systems operating under steady-state conditions. However, the concept is also useful in helping students make sense of non-steady-state phenomena. For example, the “mass balance” concept may be applied to a model examining changes in neurotransmitter concentration within a synaptic cleft or a model considering changes in calcium ion concentration in the cytosol of skeletal muscle.

Also, by using the concept in conjunction with other core concepts or general models, students are able to gain new insights into a broader range of phenomena. For example, by using “mass balance” in conjunction with the “flow down gradients” core concept and the elastic properties of tissue general model (1, 10), students can easily examine the factors that contribute to various phenomena in the cardiovascular system. The elastic properties of tissue general model (1) describe an elastic structure in terms of an unstressed length or volume and recoil when it is displaced from its unstressed state. Thus the pressure in a vessel depends on the vessel volume and recoil of the vessel wall.

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### Table 5. Responses to the five questions rating the importance of components of the mass balance conceptual framework

| Question                                                                 | Rating | Average |
|--------------------------------------------------------------------------|--------|---------|
| Q6. How important is it that your students are able to apply the concept of mass balance as described above? |        | 4.03    |
| Q8. How important is it that your students can apply the core concepts of mass balance to the case of LIQUIDS (as described above - MB-A1)? |        | 4.24    |
| Q9. How important is it that your students can apply the core concept of mass balance to the case of GAS (as described above - MB-A2)? |        | 4.15    |
| Q10. How important is it that your students can apply the core concept of mass balance to the case of SOLUTE (as described above - MB-A3)? |        | 4.21    |
| Q11. How important is it that your students can apply the core concept of mass balance to the case of SOLID (as described above - MB-A4)? |        | 3.51    |

/5 - Essential/4 - /3 - /2 - /1 - Unimportant.

### Table 6. A sample of respondents written comments about the mass balance conceptual framework

| Category                        | n | Examples                                                                 |
|---------------------------------|---|-------------------------------------------------------------------------|
| No comment                      | 6 | “N/A”                                                                  |
|                                 |   | “None”                                                                 |
| Well done                       | 6 | “No changes - this is well defined/explained”                          |
|                                 |   | “The wording is very clear.”                                           |
| Commentary about core concept    | 5 | “It is fine, but for medical students it would be somewhat overwhelming” |
|                                 |   | “I don’t cover this topic”                                             |
|                                 |   | “No specific changes but I think conveying the thought that the process of measuring individual components of system can be challenging is important.” |
| Suggestion(s) for additions     | 11| “The inclusion of physical forces (such as pressure) as a consequence of changes in amount of mass” |
|                                 |   | “Matter can enter/leave compartments through different mechanisms (depending on nature of matter i.e., gas, ion, etc.).” |
|                                 |   | “With respect to the aspects of the framework on the next page, it looks like something about solutes is missing (e.g., production (CO2, hormone, etc.) within compartment as a rate in)” |

Comments from 5 surveys were not accessible; n = 28.
same (8). The conceptual framework presented here should be one tool that can be used by both teachers and students to make sense of physiology.

**ACKNOWLEDGMENTS**

We want to acknowledge the contributions to this work made by all of our colleagues who participated in our survey.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the authors.

**AUTHOR CONTRIBUTIONS**

J.M. and H.M. conceived and designed research; J.M. and H.M. performed experiments; J.M. and H.M. analyzed data; J.M. and H.M. interpreted results of experiments; J.M. and H.M. prepared figures; J.M. and H.M. drafted manuscript; J.M. and H.M. edited and revised manuscript; J.M. and H.M. approved final version of manuscript.

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