Progressions of Conceptual Models of Cardiovascular Physiology and their Relationship to Expertise

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Abstract

The application of scientific principles in diverse science domains is widely regarded as a hallmark of expertise. However, in medicine, the role of basic science knowledge is the subject of considerable controversy. In this paper, we present a study that examines students' and experts' understanding of complex biomedical concepts related to cardiovascular physiology. In the experiment, subjects were presented with questions and problems pertaining to *cardiac output*, venous return, and the mechanical properties of the cardiovascular system. The results indicated a progression of conceptual models as a function of expertise, which was evident in predictive accuracy, and the explanation and application of these concepts. The study also documented and characterized the etiology of significant misconceptions that impeded subjects' ability to reason about the cardiovascular and circulatory system. Certain conceptual errors were evident even in the responses of physicians. The scope of application of basic science principles is not as evident in the practice of medicine, as in the applied physical domains. Students and medical practitioners do not experience the same kinds of epistemic challenges to counter their naive intuitions.

Introduction

It is widely recognized that scientific principles play a fundamental role in the organization of conceptual knowledge and procedural knowledge for effective problem solving in diverse science domains and that the use of principled knowledge is a function of expertise (e.g., Chi, Feltovich, & Glaser, 1981). However, in medicine, the role of biomedical or basic science knowledge (e.g., physiology) is a source of considerable controversy. Clinical knowledge and basic science knowledge constitute two distinct bodies of knowledge that are connected only at various discrete points (Patel, Evans, & Groen, 1989). Clinical knowledge is primarily categorical and includes a classificatory scheme for disease entities and associated clinical findings. Basic science knowledge in medicine involves the organization of biomedical models at different levels of abstraction. Basic science knowledge is not easily integrated into clinical contexts and its use frequently does not improve the diagnostic performance of either expert physician or novice medical student (Patel, et al, 1989). It is not clear whether the development of expertise in medicine reflects progressions of increasingly elaborate and refined causal models built around basic science principles.

Empirical studies of many different domains in science indicate that students begin their study of science with strongly held misconceptions of phenomena (Eylon & Linn, 1988). These misconceptions are grounded in experience and are extremely resistant to change, even after instruction. The large majority of science concept learning research has addressed issues in the physical sciences. The relatively few studies in the biomedical sciences have yielded similar results, for example, documenting misconceptions in students' causal understanding of the structure and function of the heart (Feltovich, Spiro, & Coulson, 1989) and in the application of pulmonary concepts in clinical contexts (Patel, Kaufman, & Magder, 1991). These findings underscore a need to characterize students' and physicians' understanding of basic science concepts in different domains of medicine.

Conceptual understanding of physical or biological systems can be characterized in term of progressions of mental models (e.g., Forbus & Gentner, 1986). Mental models refer to the internal models of systems individuals develop from interacting with these systems (Norman, 1983). We can characterize subjects' models and elucidate aspects of subjects' representations that are flawed in terms of the structure and function of a system or in terms of the inferences used to evaluate the behavior.

The purpose of this study is to characterize students' and experts' understanding of concepts related to the mechanical properties of cardiovascular physiology. Specifically, the investigation focuses on the determinants of *cardiac output* (the blood ejected by the heart per unit time), and *venous return* (the blood returning to the heart per unit time). The study addresses individual differences in conceptual understanding and the progression of mental models of the cardiovascular system of subjects at different levels of expertise.

Cardiovascular Physiology

The regulation of cardiac output is a complex abstract topic, which unlike most subject domains in physiology, is lacking in explicit structure-function correspondences. *Cardiac output* is the total amount of blood pumped by the heart per unit time. It is a product of two factors, *heart rate* and *stroke volume*. Heart rate is the number of contractions or heart beats per minute. Stroke volume is the amount of blood ejected by the ventricle during contraction. Stroke volume is determined by three factors: 1) *preload*, which refers to the initial stretch of the cardiac muscle before contraction; 2) *afterload*, which is the tension in the cardiac fibres and is a force in which the heart must pump against; and 3) *contractility*, the functional state of the heart muscle that is defined by the rate and extent of shortening for a given afterload and preload. Preload and contractility are positively associated with stroke volume and therefore cardiac output. Afterload is negatively associated with stroke volume and cardiac output.

Venous return is the amount of blood returning to the heart per unit time. It is a determined primarily by *vascular compliance* and by *venous resistance*. Vascular compliance refers to the ability of a vessel to distend to accommodate more blood volume per unit pressure. Vascular resistance is the opposition to blood flow offered by the vessels and is primarily determined by the radius of the vessel and the viscosity of the blood. *Mean systemic pressure* is a measure that is determined by stressed volume and compliance and is independent of cardiac function. It is the driving pressure for venous return. Stressed volume is the volume that actually stretches the elastic walls of vessels and thus produces pressure in the vasculature.

The circulatory system is a closed system and therefore the blood pumped out by the heart must inevitably return to the heart. Over time, cardiac output has to equal venous return. Cardiac function mainly effects venous return by changing the outflow pressure for the peripheral vasculature. Venous pressures from output are independent from the heart because cardiac volume is small relative to peripheral blood volume.

A causal influence network was generated to represent the set of entities and relations involved in the problem set. This is illustrated in figure 1. This representation is similar to ones used in qualitative simulation of physical systems (e.g., Forbus & Gentner, 1986). The figure represents directional functional dependencies between the variables included in the study. The variables represent quantities, that when changed, can initiate a process that will effect other variables in predictable ways. A variable can exert a positive, negative or neutral influence on another variable. There are relationships that are not explicitly represented and can be deduced from the network. The network, however, does not explicitly reflect temporal relations or enabling conditions that can delimit the circumstances when an influence can be exerted or how to resolve ambiguities from multiple simultaneous influences.

Methods

The subjects consisted of 15 volunteers at several levels of expertise. The subjects included: one student who had completed a degree in biology; students from each of the four years of medical school; two physicians who were completing a cardiology resident training program; an expert physiologist, a cardiologist in private practice, and an academic cardiologist who divides his time between research and hospital practice.

The materials consisted of 49 questions and problems, including (1) 35 basic-level questions about specific factors pertaining to cardiac output, venous return, and pressure-volume and pressure-flow relationships, as well as questions intended to assess the degree to which subjects have integrated coherent models of the circulatory system; and (2) 12 situated problems in which these concepts are to be applied. These include brief clinical and applied physiology problems designed to assess the subjects' ability to recognize the conditions of applicability and use these concepts in context. Subjects were presented with a series of questions and problems on cue cards, one at a time. They were asked to read the question out loud and "talk-aloud", and answer the questions as completely as possible. The subjects were tested one at a time and each session was audio taped and transcribed for analysis. This paper focuses predominantly on subjects' responses to the basic-level questions. A more detailed discussion of the experiment and results can be found in Kaufman, Patel, and Magder (1992).

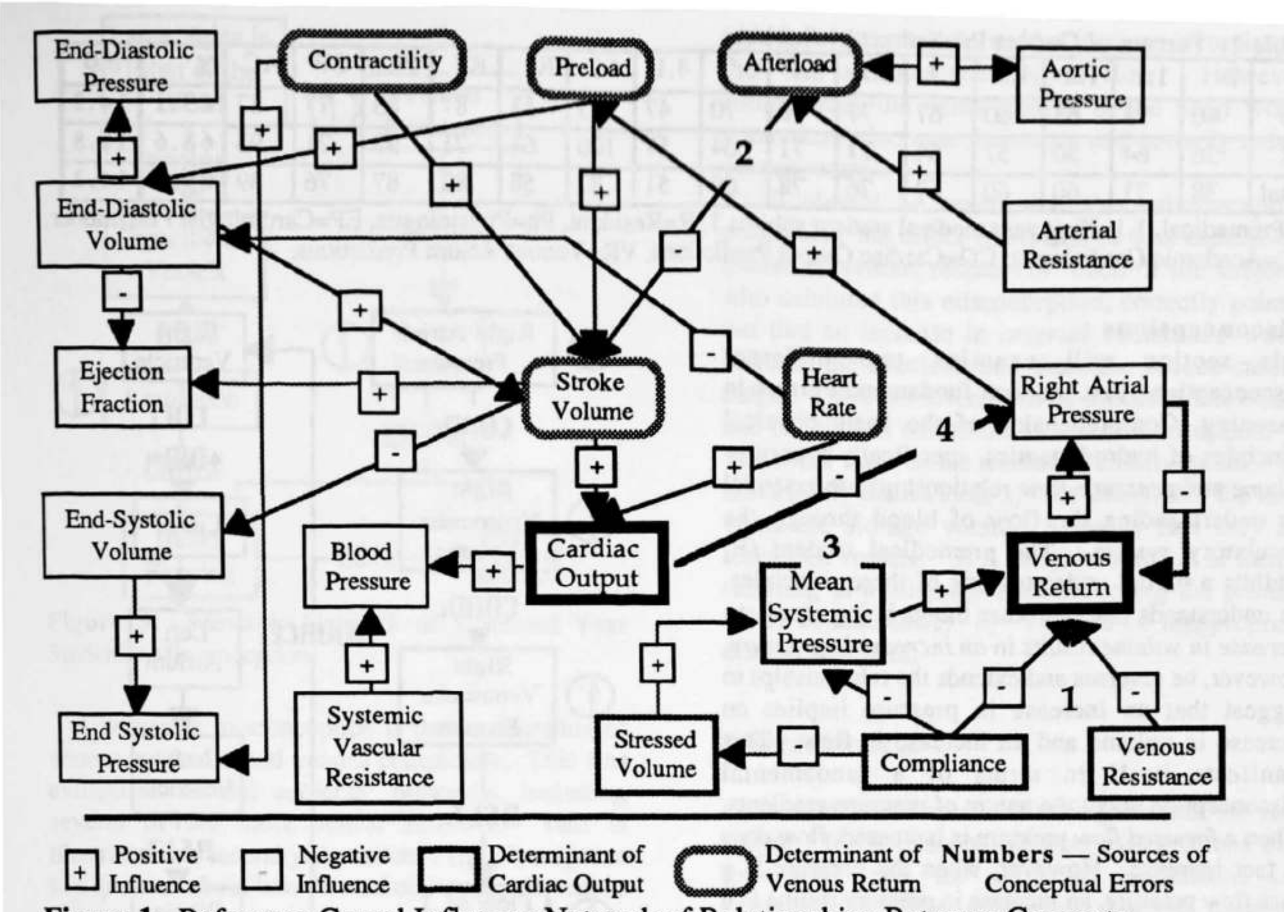

Figure 1: Reference Causal Influence Network of Relationships Between Concepts.

For each problem, a *reference model* response was prepared with the assistance of a consulting expert cardiologist and was used to assess the answers of each subject. Many of the questions required predictions. These took the form of how a particular change in state would affect the value of some measure. For example, a question asked "how does a large increase in *afterload* affect *cardiac output*". The possible responses are *no change, increases, decreases.* Subjects were required to make predictions in 29 of the questions, for a total of 45 predictions. The probability of randomly generating a correct prediction was approximately 30%. Incorrect responses were categorized according to the difference in direction of prediction. Patterns of subjects responding across questions provided us with information concerning gaps in knowledge and misconceptions. Semantic networks were also used to represent subject's causal explanations for individual questions (Groen & Patel, 1988).

The typology of relations used in semantic networks included in this paper are: **ACT**–engages in an action or process, **CAU**–causality, **COND**–directional conditionality, ***DIR***–direction, **EQUIV**–equivalent in some property, **IDENT**–identity, **LOC**–location, **RSLT**–result of an action, and arrows indicate directionality. A causal influence network, representing subjects' beliefs concerning relationships between variables, was also generated for each subject and then was contrasted with the reference network. This method allows us to characterize aspects of their mental models' of the mechanics of the cardiovascular system.

Results and Discussion

There was a general tendency for an increase in correct predictions with expertise. The medical students predicted a mean of 68.1% (sd=10) of the correct responses. The five more advanced subjects accurately predicted 78.2% (sd=12.5). There were considerable individual differences. The premedical student generated the fewest total correct predictions (38%) and the academic cardiologist (89%) and the physiologist (87%) correctly predicted the highest percentage of responses. Most students tended to have somewhat more difficulty with the venous return questions than cardiac output questions. The expert subjects responded with greater consistency across question types. Surprisingly, a fourth year student and a resident predicted only 51% and 58% of the correct responses, respectively.

Table 1: Percent of Correct Predictions by Subject

	P	1.1	1.2	1.3	2.1	2.2	3.1	3.2	4.1	4.2	R1	R2	Ph	CP	AC	$\bar{X}$	SD
CO	40	73	63	60	67	77	80	70	47	73	53	87	83	77	87	**69.1**	**14.2**
VR	36	64	50	57	64	71	71	64	57	100	64	71	93	71	93	**68.6**	**16.8**
Total	38	71	60	60	67	76	78	69	51	82	58	82	87	76	89	**69.5**	**14.2**

P=Premedical, 1.1=First year medical student subject 1, R=Resident, Ph=Physiologist, EP=Cardiologist Practitioner, AC=Academic Cardiologist. CO=Cardiac Output Predictions, VR=Venous Return Predictions.

Misconceptions

This section will examine two different misconceptions that produce fundamental errors in reasoning. Comprehension of the basic physical principles of hydrodynamics, specifically *pressure-volume* and *pressure-flow* relationships are essential for understanding the flow of blood through the circulatory system. The premedical student (P) exhibits a partial understanding of these principles. He understands that, all other things being equal, *an increase in volume* results in *an increase in pressure*. However, he reverses and extends the relationships to suggest that an increase in pressure implies an increase in volume and an increase in flow. This manifests itself in terms of a fundamental misconception about the nature of pressure-gradients. When a *forward flow* pressure is increased, flow does in fact increase. However, when the pressure is a *back flow* pressure, an increase in pressure results in a decrease in flow because the pressure gradient is narrowed. This is illustrated in a semantic network representation of the subjects' response to a question that asks "what happens when right atrial pressure rises to equal the mean systemic pressure" (Figure 2).

When right atrial pressure rises to equal the mean systemic pressure, the pressure gradient for venous return becomes zero and flow stops. The subject erroneously predicts an increase in flow that propagates throughout the system. The network illustrates that the subject possesses a mental model of the circulatory system and can envision the consequences of the effect of a change in state, however erroneously. The subject demonstrated in many questions that he had an adequate structural representation of the system, but repeatedly made the same kind of error related to pressure gradients.

There are invariably multiple sources of converging knowledge that comprise misconception. In this case, they include, the reversal of a directional relationship (increase in volume leads to an increase in pressure) and failure to differentiate between a driving pressure and a back pressure that opposes flow. This fundamental misconception was not characteristic of any of the other subjects.

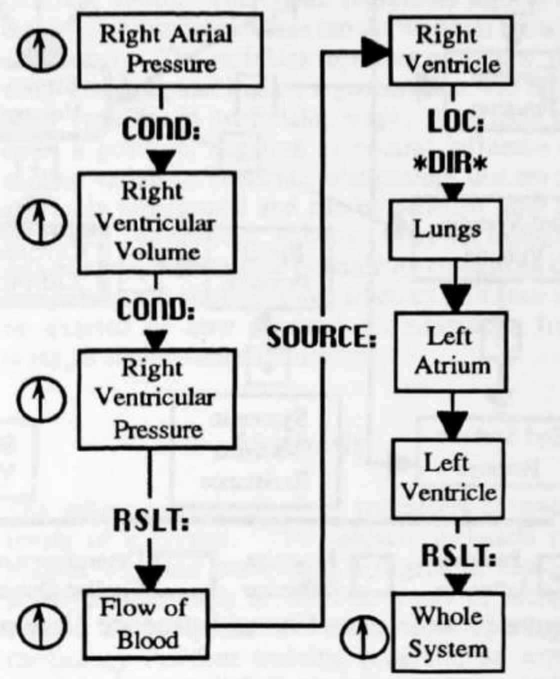

Figure 2. Semantic Network illustrating a Premedical Student's Misconception .

Many misconceptions are grounded in experience and reflect an acceptance of the primacy of experience and intuition over counter-intuitive formal teachings. However, formal learning can also result in the development of significant misconceptions. Resistance is a concept that is well rooted in experience, in the sense that resistance means the slowing down of some process (diSessa, 1983). The most important determinants of venous return are compliance and resistance. Compliance refers to the distensibility of a vessel and its ability to store blood. Venous resistance is primarily a function of the radius of the vessel. An increase in compliance increases the volume storage capacity of the vessel and therefore decreases venous return. Likewise an increase in resistance impedes the flow of blood and slows venous return. It makes sense that an increase in resistance would decrease the diameter of a tube and reduce its compliance. However, they are physiologically independent.

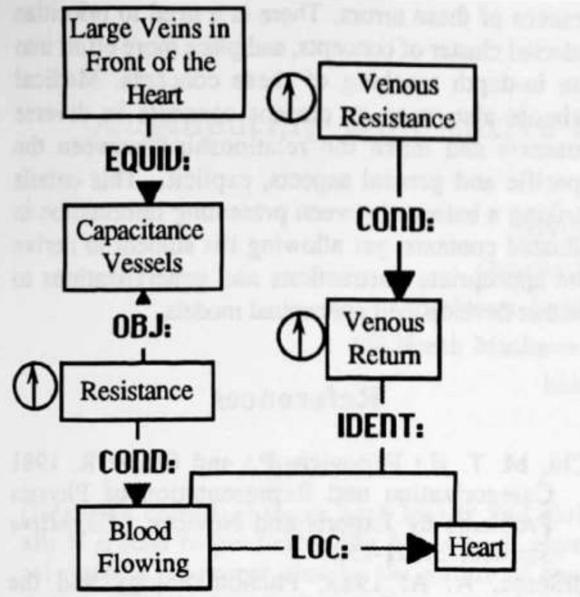

Figure 3. Semantic Network of a Second Year Student's Misconception

A pervasive misconception is the confounding of venous resistance and venous compliance. This was evident in several subjects' protocols, including several of the more senior subjects. This is illustrated in a second year student's (M2.1) response to a question about how "a marked increase in venous resistance affects venous return and cardiac output". The subject reasons that since the large veins are storage vessels, an increase in resistance would diminish storage capacity and increase blood flowing back to the heart. The most significant error here is that the large veins are storage vessels. It is commonly taught that veins are "storers of blood". In fact the large veins are downstream from the capacitance vessels, (the venules are compliance vessels) and are in effect resistance vessels that are critically important in determining blood flow.

Six out of fifteen of the subjects exhibited aspects of this misconception. It is predominantly the more advanced subjects that were most affected by this pattern of thinking. In fact both residents responded to some of the questions in a manner that would indicate that they could not completely disambiguate the effects of compliance from venous resistance. This is in evidence in the response of a resident (R2) to a question concerning the effects of compression of the veins leading to the heart on cardiac output. The subject predicts that this will greatly increase cardiac output. He applies an inappropriate analogy from a common clinical situation whereby the diaphragm is compressing the abdominal structures. This situation is typical of many medical conditions, such as asthma, where you get a sudden increase in respiratory rate and an increased blood flow. However, compressing the veins leading to the heart would dramatically increase resistance and severely reduce venous return.

It should be noted that this misconception concerning the effect of resistance was exclusively related to venous resistance. Each of the subjects, who exhibited this misconception, correctly pointed out that an increase in *arterial resistance* would increase the afterload and therefore reduce cardiac output. There are several bits of erroneous knowledge and beliefs that contribute to this misconception: 1) The belief that venous resistance and compliance are inextricably intertwined; 2) The notion that the large veins are storage vessels, when in fact they are resistance vessels; 3) A malprioritization of factors resulting in a misjudgment concerning the primary effect of resistance; 4) The use of inappropriate clinical analogies.

Mental Models

Causal influence networks were generated for each subject. The correspondences between relations were generated from the subjects' predictions and explanations. The premedical student correctly predicted only 38% of the correct responses. The effect of the pressure-volume misconception is evident in many of the relationships expressed. In general, any of the variables that suggest an increase in tension, resistance, or pressure (e.g., contractility, afterload) is believed to propagate an increase in volume or in flow.

In general, the causal influence networks of the other subjects indicated an increase in conceptual understanding with expertise. The subjects were able to qualitatively derive most behavioral states from changes in quantities to variables. With the exception of the physiologist and the academic cardiologist, each subject demonstrated a partial understanding of the mechanics of the cardiovascular system, exhibiting specific local deficits in their mental models. Figure 1 illustrates the sources of four conceptual errors. The first error relates to the confounding of venous resistance and compliance and was discussed in detail in the last section.

The second conceptual error was evident in the responses of a fourth year student who correctly predicted only 51% of the correct outcomes. It was evident from the subject's explanations that he understood most of the concepts and could apply them in more complex situations. The source of most of the subject's conceptual difficulties is related to the effects of afterload, which is one of the critical determinants of cardiac output. The subject infers that afterload has no effect on stroke volume. Afterload, in fact, decreases stroke volume. The fact that the subject's model is largely coherent, and that he correctly represents the relationship between stroke volume and all other variables, serves to propagate errors throughout the system when a question involves either *afterload, aortic pressure* or *arterial resistance* as causal agents.

The third and fourth sources of conceptual errors were associated with variables related to venous return. The third error reflects a lack of understanding of a primary determinant of venous return, *mean systemic pressure*. The fourth error is related to the functional role of the right atrium as a coupling mechanism relating cardiac output and venous return. Only the academic cardiologist and the physiologist were unaffected by these conceptual errors.

In general, subjects' responses indicated a "cardiocentric" bias, explaining situations in terms of cardiac output factors and excluding venous return factors from consideration. The three experts showed differences in their conceptual understanding. For example, the physiologist could respond with considerable facility to the basic physiology questions and had great difficulty explaining the situated problems. The academic physician was the one subject who could respond to either question type with great facility. The two cardiologists responded very differently to many of the questions. The practitioner correctly predicted only 76% and the academic physician predicted 89% correct. The practitioner tended to focus on a single possible cause, while the academic cardiologist was able to generate several possible alternatives and identify the delimiting factors that could produce different results.

Conclusions

In this study, we examined the conceptual understanding of subjects at several levels of expertise of a rather complex domain, circulatory and cardiovascular physiology. The scope of application of basic science principles is not as evident in the practice of medicine, as in the applied physical domains (e.g., engineering). Students and practitioners cannot experience the same kinds of epistemic challenges to counter their naive intuitions. Consequently, even striking anomalies resulting from fundamental misconceptions can frequently go undetected, and may carry over into clinical practice. Certain conceptual errors are consequences of formal learning. It is important to identify the possible sources of these errors. There is a need to prioritize selected cluster of concepts, and place more effort into the in-depth teaching of these concepts. Medical schools also need to present concepts in diverse contexts and make the relationships between the specific and general aspects, explicit. This entails striking a balance between presenting information in situated contexts, yet allowing the student to derive the appropriate abstractions and generalizations to further develop their conceptual models.

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