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Unpacking the renal system component of the 'Structure and Function' Core Concept of Physiology by an Australian team.

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Running Head: Unpacking Structure and Function in Physiology

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New and noteworthy:

- This is the first attempt to unpack and validate the *Structure & Function* core concept in physiology with Australian educators.
- We unpacked the *Structure and Function* core concept using the renal system into themes with hierarchical levels and validated by an experienced team of Australian physiology educators.
- Our unpacking of the *Structure and Function* core concept provides a specific framework for educators to apply this important concept in physiology education.

ABSTRACT

Australia-wide consensus was reached on seven core concepts of physiology, one of which was '*Structure and Function'* with the descriptor '*Structure and function are intrinsically related to all levels of the organism. In all physiological systems the structure from a microscopic level to an organ level dictates its function*'. As a framework for the *Structure and Function* core concept, the renal system was unpacked by a team of five Australian Physiology educators from different universities and with extensive teaching experience into hierarchical levels, with five themes and twenty-five sub-themes up to 3 levels deep. Within Theme 1, the structures that comprise the renal system were unpacked. Within Theme 2, the physiological processes within the nephron such as filtration, reabsorption, and secretion were unpacked. Within Theme 3, the processes involved in micturition were unpacked. In Theme 4, the structures and processes involved in regulating renal blood flow and glomerular filtration were unpacked; and within Theme 5, the role of the kidney in red blood cell production was unpacked. Twenty-one academics rated the difficulty and importance of each theme/subtheme and results were analyzed using a one-way ANOVA. All identified themes were validated as 'essential' to 'important'/'moderately important' and rated between 'difficult' to 'not difficult'. A similar framework consisting of Structure, Physiological processes, Physical processes and Regulation can be used to unpack other body systems. Unpacking of the body systems will provide a list of what students should be taught in curricula across Australian universities and inform assessment and learning activities.

INTRODUCTION

Whilst rarely the intention of the educator, the teaching of physiology has often relied simply on students remembering facts to explain why a physiological process occurs in an organ or complex system (1). To address this difficult problem, Michael and McFarland (2) created a list of 15 core principles (‘big ideas’) in physiology from surveying physiology educators. Referred to as ‘core concepts’, these conceptual ideas are guided by expert knowledge, generalizable to many areas of the body, and will have greater longevity than memorization of specific facts (2, 3). Physiological concepts provide a scaffolding to ensure that when students learn information about physiological systems and processes within them, they can be integrated with a set of fundamental physiological principles guiding the functioning of the body. For example, ’flow down gradients’ is a fundamental principle which can be applied when discussing neuronal action potentials (in combination with the role of membranes and membrane potential), and the diffusion of electrolytes in different parts of the nephron.

Across 17 Australian Universities, the 15 core concepts developed by Michael and McFarland (2) did not map well against subject learning outcomes comprising physiology majors (4). It was speculated that many of these core concepts did not resonate with Australian physiology educators involved in writing subject learning outcomes, and to address this issue, a Delphi protocol was employed to reach Australia-wide consensus on a set of Physiology core concepts. Seven core concepts with their definitions were endorsed: *Cell Membrane, Cell-cell Communication, Movement of Substances, Structure and Function, Homeostasis, Integration* and *Physiological Adaptation* (5).

The core concept of *Structure and Function* is widely regarded as important in physiology education. In a survey of physiology educators and students reported by Stanescu et al. (6), Structure and Function was ranked as the second most important concept behind Interdependence. In our mapping study, learning outcomes from physiology majors across 17 universities mapped most commonly to Structure and Function (4). In addition to the name, Australia-wide agreement was reached on the *Structure and Function* descriptor ’*Structure and function are intrinsically related to* *all levels of the organism. In all physiological systems the structure from a microscopic level to an organ level dictates its function'* (5). the consensus that *Structure and Function* is a vital core concept in physiology, its understanding by students tends to be relatively poor. When students were asked to give an example of how structure defines function (after being asked first to give a definition of the concept), only 48% of students were able to give an accurate example of how structure affected function (7). While perhaps the varying definitions of *Structure and Function* may be contributing to this lack of understanding (8), a key issue might be a degree of vagueness inherent in the concept. As noted by Michael (8): "*structure/function… is simply a truism; we must always understand the structure generating a function in order to fully understand that function*". Therefore, how do we contextualise this concept and make it more meaningful and specific for students?

Structure and Function is also potentially the largest of all the core concepts, as a separate unpacking can be applied to each system individually, namely: cardiovascular, gastrointestinal, integumentary, muscular, nervous, skeletal, renal, endocrine, reproductive and respiratory. We define "unpacking" as a method to divide a large concept into smaller facets or ideas. Herein we propose that a useful way to unpack the *Structure and Function* concept is via using a physiological system as a specific example. Therefore, the aim of this study was to unpack and validate *Structure and Function* in reference to the renal system and in the process create a structural framework which will allow students to see how *Structure and Function* is dictated at the system, organ, tissue, and molecular levels, and provide educators with a framework to unpack other systems.

MATERIALS AND METHODS

We unpacked and validated *Structure and Function* in reference to the renal system into hierarchical levels, with five themes and 25 subthemes that were up to three levels deep using a framework of Structures, Physiological processes, Physical processes and Regulation. The method followed was adapted from that of Michael et al. (9).

Unpacking Team & Protocol:

Structure and Function was validated as a core physiology concept using the Delphi method described elsewhere (5). To contextualise this concept, we decided to apply a framework to a single physiological system, the renal system, which would aid in unpacking of the rest of the systems. A team of five educators, each with a minimum of nine years' experience teaching physiology unpacked the renal system into five main themes under the framework of Structures, Physiological processes, Physical processes, and Regulation (with two regulations separated), each with subthemes up to three levels deep.

Survey participants

To validate the importance of each theme and subtheme created by the unpacking team, the unpacked themes and subthemes were entered into a Qualtrics survey and a link sent out to 25 physiology educators from the Task force which had previously completed the Delphi protocol (5), of which 21 completed the survey. The Task force participants work at 21 different Australian universities located in: New South Wales (four), Victoria (four), Western Australia (four) and Queensland (four), South Australia (three), Tasmania (one) and the Australian Capital Territory (one). Task force members had taught undergraduate physiology for a mean of 16.4 years (standard deviation: 7.1 years, range: 7-31 years), and had an average of 52% allocation of time/workload to teaching (standard deviation: 18%, range: 20-80%). All participants had experience designing curriculum and assessments in physiology. Participants had experience teaching physiology into a range of degrees, such as biomedical sciences, health sciences, exercise and sport science, science, medical science, medicine, nursing, paramedicine, nutrition and dietetics, across a range of educational delivery strategies (lectures, tutorials, workshops, and practicals).

Survey

Survey respondents from the Task force were asked to rate each theme and subtheme on a 5-point Likert scale for level of importance for the students to understand (1=Essential, 2=Important, 3=Moderately Important, 4=Slightly Important and 5=Not Important) and level of difficulty for students to comprehend (1=Very Difficult, 2= Difficult, 3=Moderately Difficult, 4=Slightly Difficult and 5=Not Difficult). The detailed description of these themes and subthemes are included in Tables 1 and 2.

Statistical Analyses

Survey responses were analyzed with a one-way ANOVA to compare between and within concept responses. Bonferroni post hoc analysis were performed to compare individual comparisons between themes and subthemes. All statistical analyses were performed in SPSS (IBM Corp, Version 27.0. Armonk, NY, USA), and figures were made in Microsoft Excel (Excel 2019, Microsoft Corporation Redmond, WA, USA). Data are presented as mean with standard deviation (SD), median, and interquartile range (IQR).

RESULTS

Survey respondents:

21 members from the Task force completed the survey.

Unpacking and Survey Results

Five themes and twenty-five subthemes that were up to three levels deep were unpacked by the Task force members (Tables 1 and 2). Five main themes were highlighted: Theme 1 - renal system structures; Theme 2 - the processes of glomerular filtration, tubular reabsorption and tubular secretion and their contribution to extracellular fluid composition, volume and pH; Theme 3 - micturition; Theme 4- structures and processes in regulating renal blood flow, glomerular filtration and systemic blood pressure; and Theme 5, the role of the kidney in red blood cell production.

Ranking of Theme Importance

The 5 themes identified within the renal system were rated on average between 'essential' to 'important'/'moderately important'. When accounting for all items within each theme, Theme 1 (renal system structures) ranked the highest for importance (1.40 ± 0.68; mean ± SD), and Theme 3 (micturition) ranked the lowest (2.21 ± 0.87) but still deemed 'important'/'moderately important' overall. Theme 2 (1.77 ± 0.81) which examined nephron-based processes, and Theme 4 (1.8 ± 0.72) which examined regulation of blood flow and glomerular filtration, were both rated between 'essential' to 'important' on average. Themes 2 and 4 were more important than Themes 3 (micturition, $p<0.01$) and 5 (2.16 ± 1.01; kidney and red blood cell production, $p<0.01$), but were not perceived as important as Theme 1 (renal structures, $p<0.01$). Descriptive data showing the distribution of importance ratings of the main theme descriptors only (Theme 1, 2, 3, 4, and 5 from Table 1) are displayed Figure 1.

Within Themes 1, 3 and 4, subthemes were not rated significantly different from each other ($p>0.05$) regarding importance. Theme 2 had the most variability in importance rating where many of the subthemes were significantly different from each other. For example, subtheme 2.1 ("The kidneys receive about 20% of cardiac output and are supplied by the renal arteries.") and 2.2 ("Renal arteries successively divide eventually forming afferent arterioles") were both rated less important than the theme description (2 - Extracellular composition, volume and pH is maintained by the kidneys through physiological processes of glomerular filtration, tubular reabsorption and tubular secretion), and subthemes 2.2.2, 2.3, 2.3.1, 2.3.2, 2.3.3 and 2.3.4 ($p<0.05$). In theme 5, subtheme 5.1.1 ("EPO is produced primarily by interstitial fibroblasts in the kidney in the adult and to a lesser extent hepatocytes. The liver is the main site of EPO production in the fetal and perinatal periods.") was rated as less important than the theme 5 description and subtheme 5.1 (The kidney responds to chronic low levels of circulating blood oxygen by secreting Erythropoietin (EPO), $p<0.05$).

Rating of Theme difficulty

In terms of perceived difficulty for students, the main Themes were ranked on average between 'difficult' and 'not difficult' when accounting for all items within each theme, the most difficult concept identified was Theme 4, which described regulation of renal blood flow, glomerular filtration and blood pressure, and was ranked between 'difficult' to 'moderately difficult' (2.92 ± 0.94) and was perceived to be significantly more difficult than all other themes ($p<0.01$). Theme 1, which described structures of the renal system (4.31 ± 0.75), and Theme 3 (micturition; 4.16 ± 0.80) were rated as between 'slightly difficult' and 'not difficult' and were not significantly different from each other ($p>0.05$), however, both were rated as less difficult than Themes 2, 4, and 5 ($p<0.01$). Theme 2 (3.33 ± 1.02) was significantly different to all other Themes ($p<0.01$), and Theme 5 (3.73 ± 0.78) was significantly different to all other Themes ($p<0.05$). Descriptive data showing the distribution of importance ratings of the main theme descriptors only (theme 1, 2, 3, 4, and 5. from Table 2) and displayed in Figure 2.

Within themes 4 and 5, none of the subthemes were rated differently to other subthemes in terms of difficulty ($p>0.05$). Within theme 1, subtheme 1.2.2 (“Each nephron consists of a renal corpuscle comprising a glomerulus and a glomerular capsule followed by a renal tubule that is continuous with the glomerular capsule”) was rated as more difficult than theme 1 ($p<0.05$). Within theme 3, subtheme 3.2 (“Emptying of the bladder involves contraction of the detrusor muscle and relaxation of the internal sphincter”) was rated as more difficult than theme 3 ($p<0.05$). Similar to the importance ratings, theme 2 had the greatest variability in difficulty rating, with subtheme 2.1 (“The kidneys receive about 20% of cardiac output and are supplied by the renal arteries”) being significantly less difficult than subthemes 2.2.2, 2.2.4, 2.3.1, 2.3.2, 2.3.3 ($p<0.05$).

Additional comments from Survey Respondents

The questionnaire contained an open-answered question where participants could suggest improvements to the *Structure and Function* concept. Table 3 lists these responses.

Table 1: Level of importance for students to understand as rated by Task force members (1 = essential, 2 = important, 3 = moderately important, 4 = slightly important, 5 = not important)

Themes and subthemes	n	Mean	SD	Median	IQR
1. Comprises kidneys, ureters, a urinary bladder and a urethra	20	1.10	0.45	1.00	0.00
1.1 The kidney is structurally and functionally divided into a cortex and a medulla	20	1.55	0.76	1.00	1.00
1.2 Nephrons are the functional units of the kidney and each kidney comprises approximately 1 million nephrons.	20	1.10	0.45	1.00	0.00
1.2.1 Nephrons are categorised according to their positioning and structure as cortical or Juxta medullary.	20	1.95	0.76	2.00	1.75
1.2.2 Each nephron consists of a renal corpuscle comprising a glomerulus and a glomerular capsule followed by a renal tubule that is continuous with the glomerular capsule.	20	1.45	0.69	1.00	1.00
1.2.3 The renal tubule from the glomerular capsule extends to the proximal convoluted tubule, the loop of Henle, distal convoluted tubule, and the collecting duct.	20	1.30	0.57	1.00	0.75
1.2.4 The collecting ducts collectively form renal pyramids and urine flows from here into the renal pelvis, ureter and on into the urinary bladder where it is held until micturition.	20	1.35	0.67	1.00	0.75
2. Extracellular composition, volume and pH is maintained by the kidneys through physiological processes of glomerular filtration, tubular reabsorption and tubular secretion.	21	1.14	0.36	1.00	0.00
2.1 The kidneys receive about 20% of cardiac output and are supplied by the renal arteries.	20	2.45	0.69	2.00	1.00
2.2 Renal arteries successively divide eventually forming afferent arterioles.	20	2.65	0.88	2.50	1.00
2.2.1 The afferent arteriole delivers blood to the glomerulus where small particles are filtered under pressure through filtration slits comprising fenestrations with overlying podocytes.	20	1.65	0.67	2.00	1.00
2.2.2 Filtration pressure is determined by the sum of systemic hydrostatic pressure, opposing capsular hydrostatic pressure and the oncotic pressure of the glomerulus	20	1.55	0.69	1.00	1.00
2.2.3 The efferent arteriole that leaves the glomerulus then forms low pressure capillary beds that entwine and are closely associated with, the renal tubule of each nephron known as peritubular capillaries.	20	2.30	0.98	2.00	1.00
2.2.4 The vasa recta in the medulla, also formed from efferent arterioles, are closely associated with the juxta medullary nephrons and play an important role in the in establishing a medullary osmotic gradient.	20	2.30	0.66	2.00	1.00
2.3 Filtrate moves from the glomerular capsule into the renal tubule where the filtrate composition is refined, and volume modified via tubular reabsorption and tubular secretion.	21	1.52	0.68	1.00	1.00

2.3.1 Tubular reabsorption (from tubule to blood) and tubular secretion (from blood to tubule) involves passive and active transport mechanisms and the exchange of water and solute particles between tubular cells and surrounding capillaries.	21	1.48	0.60	1.00	1.00
2.3.2 Balance of tubular transport in proximal tubule (bulk transport), Loop of Henle (counter-current exchange), distal tubule and collecting duct (fine tuning) determine the excretion of substances.	21	1.48	0.51	1.00	1.00
2.3.3 Reabsorption of sodium and water in the collecting duct is under the influence of the hormones Aldosterone and Antidiuretic hormone, respectively.	21	1.29	0.46	1.00	1.00
2.3.4 Urine in the collecting ducts flows into the renal pelvis (from the renal pyramids) and then through the ureters into the urinary bladder.	20	1.55	0.60	1.50	1.00
3. Micturition is the term used to describe the emptying of the bladder	20	2.25	1.16	2.00	2.00
3.1 Stretching of the bladder wall, as urine accumulates, initiates the micturition reflex and its emptying.	20	2.15	0.75	2.00	0.75
3.2 Emptying of the bladder involves contraction of the detrusor muscle and relaxation of the internal sphincter.	20	2.20	0.77	2.00	1.00
3.3 Micturition can be delayed through voluntary control of the external sphincter.	20	2.25	0.79	2.00	1.00
4. Between the afferent arteriole and the distal convoluted tubule lies the Juxta glomerular apparatus (JGA) which plays a critical role in regulating renal blood flow, glomerular filtration and systemic blood pressure.	20	1.55	0.60	1.50	1.00
4.1 The JGA comprises the macula densa, extra glomerular mesangial cells and glandular cells.	20	2.05	1.00	2.00	2.00
4.1.1 Glandular cells are specialized smooth muscle cells mainly in the walls of the afferent arterioles that synthesize, store, and secrete the enzyme renin, and is involved in the regulation of systemic blood pressure via the renin-angiotensin-aldosterone mechanism.	20	1.70	0.66	2.00	1.00
4.2 Intrinsic and extrinsic mechanisms provide regulation of Glomerular Filtration Rate (GFR).	21	1.57	0.51	2.00	1.00
4.2.1 Autoregulation (intrinsic) involving tubule glomerular feedback and myogenic reflexes enables constant renal blood flow and GFR.	21	1.90	0.70	2.00	1.00
4.2.2 Extrinsic hormonal and neural input to the kidney maintains GFR.	21	2.00	0.71	2.00	1.00
5. The kidney is critically important in red blood production in the adult.	21	1.57	0.60	2.00	1.00
5.1 The kidney responds to chronic low levels of circulating blood oxygen by secreting Erythropoietin (EPO).	20	1.65	0.67	2.00	1.00
5.1.1 EPO is produced primarily by interstitial fibroblasts in the kidney in the adult and to a lesser extent hepatocytes. The liver in the main site of EPO production in the fetal and perinatal periods.	20	3.10	0.91	3.00	1.75

5.1.2 EPO is secreted into the blood circulatory system and targets erythroid progenitor cells in the bone marrow to stimulate red blood cell production (erythropoiesis) and acts to protect circulating red blood cells from destruction.	20	2.35	0.99	2.00	1.00

Table 2: Level of difficulty for students to understand as rated by Task force members (1=Very Difficult, 2= Difficult, 3=Moderately Difficult, 4=Slightly Difficult and 5=Not Difficult)

Themes and Subthemes	**n**	**Mean**	**SD**	**Median**	**IQR**
1.Comprises kidneys, ureters, a urinary bladder and a urethra	20	4.95	0.22	5.00	0.00
1.1 The kidney is structurally and functionally divided into a cortex and a medulla	20	4.65	0.59	5.00	1.00
1.2 Nephrons are the functional units of the kidney and each kidney comprises approximately 1 million nephrons.	20	4.60	0.50	5.00	1.00
1.2.1 Nephrons are categorised according to their positioning and structure as cortical or Juxta medullary.	20	4.00	0.73	4.00	0.00
1.2.2 Each nephron consists of a renal corpuscle comprising a glomerulus and a glomerular capsule followed by a renal tubule that is continuous with the glomerular capsule.	20	3.80	0.70	4.00	1.00
1.2.3 The renal tubule from the glomerular capsule extends to the proximal convoluted tubule, the loop of Henle, distal convoluted tubule, and the collecting duct.	20	4.05	0.94	4.00	1.00
1.2.4 The collecting ducts collectively form renal pyramids and urine flows from here into the renal pelvis, ureter and on into the urinary bladder where it is held until micturition.	20	4.10	0.64	4.00	0.75
2. Extracellular composition, volume and pH is maintained by the kidneys through physiological processes of glomerular filtration, tubular reabsorption and tubular secretion.	20	3.15	0.67	3.00	1.00
2.1 The kidneys receive about 20% of cardiac output and are supplied by the renal arteries.	20	4.35	0.67	4.00	1.00
2.2 Renal arteries successively divide eventually forming afferent arterioles.	20	4.20	0.83	4.00	1.75
2.2.1 The afferent arteriole delivers blood to the glomerulus where small particles are filtered under pressure through filtration slits comprising fenestrations with overlying podocytes.	20	3.45	0.83	3.00	1.00
2.2.2 Filtration pressure is determined by the sum of systemic hydrostatic pressure, opposing capsular hydrostatic pressure and the oncotic pressure of the glomerulus	20	2.60	0.94	3.00	1.00
2.2.3 The efferent arteriole that leaves the glomerulus then forms low pressure capillary beds that entwine and are closely associated with, the renal tubule of each nephron known as peritubular capillaries.	20	3.45	0.69	3.00	1.00

2.2.4 The vasa recta in the medulla, also formed from efferent arterioles, are closely associated with the juxta medullary nephrons and play an important role in the in establishing a medullary osmotic gradient.	20	2.65	0.93	3.00	1.00
2.3 Filtrate moves from the glomerular capsule into the renal tubule where the filtrate composition is refined, and volume modified via tubular reabsorption and tubular secretion.	21	3.43	0.87	3.00	1.00
2.3.1 Tubular reabsorption (from tubule to blood) and tubular secretion (from blood to tubule) involves passive and active transport mechanisms and the exchange of water and solute particles between tubular cells and surrounding capillaries.	21	2.76	0.89	3.00	1.50
2.3.2 Balance of tubular transport in proximal tubule (bulk transport), Loop of Henle (counter-current exchange), distal tubule and collecting duct (fine tuning) determine the excretion of substances.	21	2.48	0.75	3.00	1.00
2.3.3 Reabsorption of sodium and water in the collecting duct is under the influence of the hormones Aldosterone and Antidiuretic hormone, respectively.	21	3.19	0.81	3.00	1.00
2.3.4 Urine in the collecting ducts flows into the renal pelvis (from the renal pyramids) and then through the ureters into the urinary bladder.	20	4.35	0.75	4.50	1.00
3. Micturition is the term used to describe the emptying of the bladder	20	4.85	0.37	5.00	0.00
3.1 Stretching of the bladder wall, as urine accumulates, initiates the micturition reflex and its emptying.	20	4.05	0.83	4.00	2.00
3.2 Emptying of the bladder involves contraction of the detrusor muscle and relaxation of the internal sphincter.	20	3.85	0.75	4.00	0.75
3.3 Micturition can be delayed through voluntary control of the external sphincter.	20	3.90	0.79	4.00	0.75
4. Between the afferent arteriole and the distal convoluted tubule lies the Juxta glomerular apparatus (JGA) which plays a critical role in regulating renal blood flow, glomerular filtration and systemic blood pressure.	20	2.95	0.76	3.00	0.00
4.1 The JGA comprises the macula densa, extra glomerular mesangial cells and glandular cells.	20	3.40	0.94	3.00	1.00
4.1.1 Glandular cells are specialized smooth muscle cells mainly in the walls of the afferent arterioles that synthesize, store, and secrete the enzyme renin, and is involved in the regulation of systemic blood pressure via the renin-angiotensin-aldosterone mechanism.	20	2.75	1.02	3.00	2.00
4.2 Intrinsic and extrinsic mechanisms provide regulation of Glomerular Filtration Rate (GFR).	21	2.86	1.01	3.00	1.00
4.2.1 Autoregulation (intrinsic) involving tubule glomerular feedback and myogenic reflexes enables constant renal blood flow and GFR.	21	2.67	0.86	3.00	1.00
4.2.2 Extrinsic hormonal and neural input to the kidney maintains GFR.	21	2.90	0.94	3.00	1.50
5. The kidney is critically important in red blood production in	21	4.24	0.70	4.00	1.00

the adult.					
5.1 The kidney responds to chronic low levels of circulating blood oxygen by secreting Erythropoietin (EPO).	20	3.95	0.60	4.00	0.00
5.1.1 EPO is produced primarily by interstitial fibroblasts in the kidney in the adult and to a lesser extent hepatocytes. The liver in the main site of EPO production in the fetal and perinatal periods.	20	3.40	0.68	3.50	1.00
5.1.2 EPO is secreted into the blood circulatory system and targets erythroid progenitor cells in the bone marrow to stimulate red blood cell production (erythropoiesis) and acts to protect circulating red blood cells from destruction.	20	3.30	0.73	3.00	1.00

Table 3: Sample of comments from Task force members about the *Structure and Function* core concept.

Supportive of unpacking	*"Good summary"*
	"Clear and well set-out format. Great work!"
	"It's easier to develop a core concept when the topic is localized/specific, rather than generalized. I liked this CC."
Suggested improvements	*"Very well appreciated and comprehensive work! I'd suggest though to keep the concepts widely applicable to different systems by crafting the themes to represent general concepts (even if applied best to the renal system). I think this could make it easier to follow it as a template for the other systems"*
	"This is one of the most challenging CC to unpack and the group have done a good job of collating the key aspects of the renal system. My concern is that this isn't what I think of when I think of structure function in a renal sense. I would be wanting my students to explicitly link structure and function in different contexts. For example, the twisting of the nephron and the proximity of the DCT and afferent arteriole as a structural feature that enables paracrine signalling and communication between different regions of the nephron. … This core concept could be improved by another block where key structure function relationships are made more explicit for students."
	"Minor point that there's nothing here about the role of the kidneys in the activation of Vit D. Might one of the headings be "The kidney as an endocrine organ" - The kidney has multiple endocrine roles; it secretes various hormones and humoral factors: in addition to EPO there are also the hormones of the renin-angiotensin system (RAS) and 1,25 dihydroxy vitamin D3."
	"I admire the way the renal system has been broken down and explained here with the structure and functional units. This is a big job to do a similar approach for all organ systems. I had thought the Structure Function CC would be more generic, rather than a broader organ by organ breakdown."

FIGURE 1

FIGURE 2

Discussion

The unpacking of the renal system provides a template to allow physiology educators to contextualise how *Structure and Function* can be facilitated across different hierarchical levels and across organ systems. By unpacking the renal system within the core concept of *Structure and Function*, we identified five themes, with the majority rated important when teaching renal physiology at Australian Universities. It was evident that renal structures were ranked the highest of importance, while the function of micturition was ranked the lowest, however, the subtheme responses were quite variable within in each main theme, indicating certain subthemes were still important even within themes which were perceived as less important by physiology educators. In terms of perceived difficulty, Theme 4 (regulation of renal blood flow, glomerular filtration and systemic blood pressure) was rated the highest in difficulty, whilst renal structures were ranked the least difficult.

The highly conceptual disciplinary nature and cognitive effort required to understand the concepts within human physiology make it one of the most challenging topics for students to understand (10). Whilst the way physiology is taught and students' approach to learning is important, it appears other reasons including a lack of familiarity, level of detail required to understand topics, and discipline specific factors are just as, if not more important (10, 11). Regardless of this, the unpacking team with a minimum of 9 years' experience in teaching physiology, found it a difficult concept to unpack as it can be applied to some extent, to every system at every level and within every process. How can we best exemplify a concept which is so commonly applicable? We decided unpacking around a single physiological system to contextualise *Structure and Function* to students and educators was the most logical approach to provide this framework. Our findings suggest that physiology which emphasizes the structural elements of the renal system are the most straightforward to highlight

*Structure and Functio*n; which is intuitive given the vital role of structure to the concept. It may also be easier for students as structural elements of the renal system are often covered in the early stages of physiology education at Australian Universities. Conversely, theme 4 (regulation of renal blood flow, glomerular filtration and systemic blood pressure) was rated (on average) the most difficult to relate to *Structure and Function*, though ratings within the subthemes did vary. This could be a reflection of the level at which this core concept is being taught, as later years within a program would demand a higher level of foundational physiological understanding. Indeed, this was reflected in one of the comments from a Task force member, who wanted more overt and detailed examples of *Structure and Function* in the nephron. This comment likely reflects deeper and more complex physiological concepts that are likely taught beyond the first year physiology curriculum in Australian universities, which often requires many body systems to be covered in a short period of time (one or two units/subjects), thus the opportunity to deliver concepts in more depth is limited (12).

Several Task force members commented on suggested improvements to the *Structure and Function* concept unpacking. Interestingly, whilst there were comments approving of the application of this concept specifically to a system and of the approach used overall, two comments implied a more "generic" approach would be more beneficial. These diverging comments may indicate that a more generalised unpacking of this concept not focused on a particular system may also be valuable to physiology educators. Michael (8) has previously proposed such a model (although not yet validated), and perhaps a generalised model combined with a system-based approach as we used in this unpacking will be more beneficial. Indeed, it is foreseeable the *Structure and Function* concept could be introduced first with a generalised model, and then developed further with a contextualised or system specific framework as we have provided in this study. Another comment suggested improvement via more "explicit" examples of the relationship between *Structure and Function*. A summarised version of this unpacking including only the most overt examples could also be considered, although what could be considered "overt" or "explicit" may require validation. However, a key benefit of the comprehensive approach used in this unpacking was the inclusion of ratings of importance; educators can view these ratings for each subtheme/item and select those with the most importance (lower numbers), as these are likely to be more overt examples of the *Structure and Function* concept. For example, within theme 2, subtheme 2.3.3 (Reabsorption of sodium and water in the collecting duct is under the influence of the hormones Aldosterone and Antidiuretic hormone, respectively), was one of the more important subthemes. This subtheme could be included and elaborated (add detail of how antidiuretic hormone inserts aquaporins allowing for greater reabsorption of water) in teaching *Structure and Function* at the level of the nephron. Therefore, the breadth and applied nature of the unpacking process to a system allows adaptability for educators to select themes/subthemes which are the most applicable for their subject. It is also important to note that the nature of the unpacking process requires relative brevity on each item; each item we unpacked could easily be elaborated on by physiology educators as required to best highlight *Structure and Function*.

Our unpacking of the renal system could be explicitly used by educators by linking these hormone functions with gross level structure (collecting duct) and molecular structure (formation of water channels through ADH, and increased sodium/potassium pump subunit aiding sodium reabsorption through aldosterone). We advocate that physiology educators can use the themes and sub-themes as a guide as to what should be taught and assessed. However, it is not intended to be prescriptive, but informative, and we envisage that the themes and sub-themes will evolve over time.

The framework provided for *Structure and Function* as we applied to the renal system could be applied to other bodily systems. Using broad categories such as Structure, Physiological processes and/or Physical processes, and Regulation allows for transfer of this framework to any physiological system. For example, the cardiovascular system could be unpacked first with the physical structures of the heart, blood vessels and components of blood (Structure). The process of excitation and myocardial contraction of different chambers of the heart could then be explored, as well as the role of pressure changes and valves with blood movement through the heart (Physiological and Physical processes). Finally, regulation of the heart and blood vessels through autonomic, endocrinological and paracrine signals could be explored from a *Structure and Function* perspective (Regulation). Teaching core physiology concepts is proposed to create a more transferable knowledge for students to learn physiology (13, 14), therefore, contextualisation of *Structure and Function* for students would aid in the goal of teaching core concepts, and physiology education more broadly. Another application of applying *Structure and Function* to a specific system such as we have with the renal system, is that it allows for reinforcement of core concepts taught previously. If students have already completed a subject which emphasizes physiological core concepts, this concept could be easily integrated into systems-based physiology subjects, both reinforcing the core concept, and integrating the new content with the existing student knowledge.

Limitations and Future Directions

Our unpacking provides a valuable and practical conceptual framework to educators and students, to explicitly teach the *Structure and Function* concept. There is, however, further scope to elaborate on the *Structure and Function* concept from an educational research standpoint. One limitation is that we have also not mapped the core concepts across curricula. Some physiology educators may be delivering core concepts across one, or multiple years of a given program. Conversely, core concepts may not be taught at all. It would be intriguing to further explore at what level these themes and physiology core concepts are currently being taught by the Task force members in Australian Universities. A limitation of our study is that we did not measure how difficult students find the *Structure and Function* concept. We measured how difficult educators perceived the themes/subthemes to be; there may be some disconnect between educators' perception of difficulty compared to the actual difficulty for students, and this would be an important future research direction.

Conclusions

As experts, physiology educators have implicit knowledge about core concepts within the physiology discipline that they can draw upon to allow for in-depth understanding. As educators, we often forget that our students are naïve learners, and, therefore, do not have the same implicit knowledge and thus need the proper scaffolding and conceptual framework to assist in the understanding of the many core concepts and their themes/subthemes. The unpacking of *Structure and Function* using the renal system as an example into themes and subthemes will help educators incorporate this concept within a course, unit, assessments, but most importantly, provide guidance to educators to make this core concept explicit for students. In the next phase of this project, the 25 academics who took part in the Delphi protocol will work with assessment experts to produce an inventory of high-order assessment items which measure attainment of the core concept themes and sub-themes and can be used for benchmarking across universities. In turn, the assessments and related unit learning outcomes will inform teaching and learning activities within the classroom.

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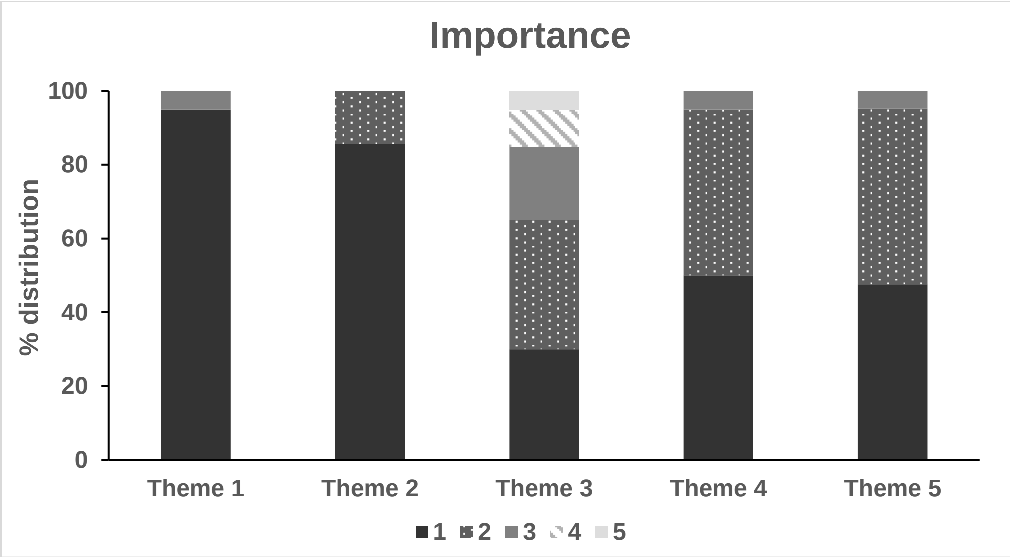
LEGENDS

Figure 1: Percentage distribution of rated importance of Themes 1-5 for the renal system. Value presented is the distribution for the main descriptor item of each theme (theme 1, 2, 3, 4, and 5 from Table 1). Scale is as follows: 1 = essential, 2 = important, 3 = moderately important, 4 = slightly important, 5 = not important. Theme 1 - structures of the renal system; Theme 2 - glomerular filtration, tubular reabsorption and tubular secretion; Theme 3 – micturition; Theme 4 – regulation of renal blood flow, glomerular filtration and systemic blood pressure; Theme 5 - role of the kidney in red blood cell production. All statistical inferences for themes/subthemes can be found within Results text.

Figure 2: Percentage distribution of rated difficulty of Themes 1-5 for the renal system. Value presented is the distribution for the main descriptor item of each theme (Theme 1, 2, 3, 4, and 5 from Table 2). Scale is as follows: 1=very difficult, 2= difficult, 3=moderately difficult, 4=slightly difficult and 5=not difficult. Theme 1 - structures of the renal system; Theme 2 - glomerular filtration, tubular reabsorption and tubular secretion; Theme 3 – micturition; Theme 4 – regulation of renal blood flow, glomerular filtration and systemic blood pressure; Theme 5 - role of the kidney in red blood cell production. All statistical inferences for themes/subthemes can be found within Results text.



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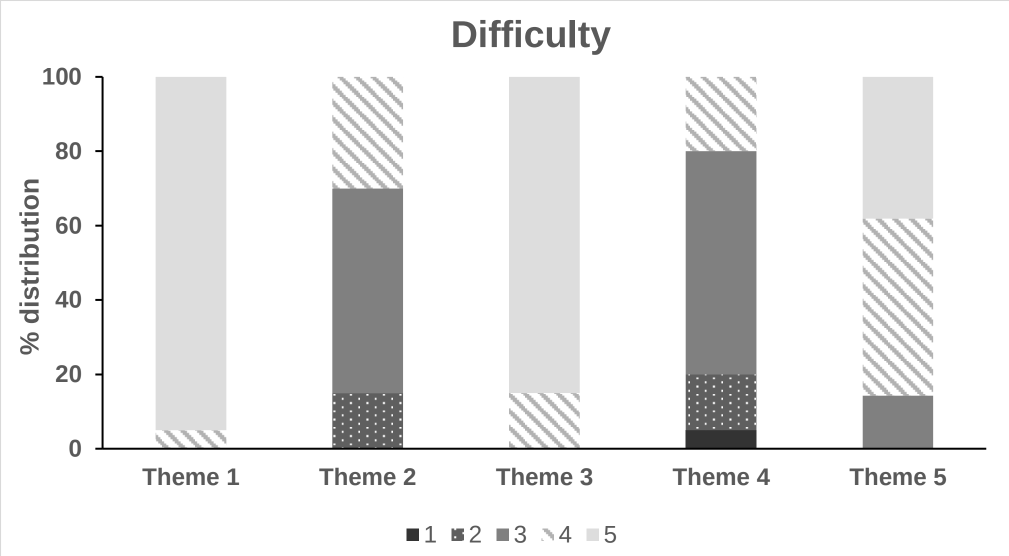

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Themes and subthemes	n	Mean	SD	Median	IQR
1. Comprises kidneys, ureters, a urinary bladder and a urethra	20	1.10	0.45	1.00	0.00
1.1 The kidney is structurally and functionally divided into a cortex and a medulla	20	1.55	0.76	1.00	1.00
1.2 Nephrons are the functional units of the kidney and each kidney comprises approximately 1 million nephrons.	20	1.10	0.45	1.00	0.00
1.2.1 Nephrons are categorised according to their positioning and structure as cortical or Juxta medullary.	20	1.95	0.76	2.00	1.75
1.2.2 Each nephron consists of a renal corpuscle comprising a glomerulus and a glomerular capsule followed by a renal tubule that is continuous with the glomerular capsule.	20	1.45	0.69	1.00	1.00
1.2.3 The renal tubule from the glomerular capsule extends to the proximal convoluted tubule, the loop of Henle, distal convoluted tubule, and the collecting duct.	20	1.30	0.57	1.00	0.75
1.2.4 The collecting ducts collectively form renal pyramids and urine flows from here into the renal pelvis, ureter and on into the urinary bladder where it is held until micturition.	20	1.35	0.67	1.00	0.75
2. Extracellular composition, volume and pH is maintained by the kidneys through physiological processes of glomerular filtration, tubular reabsorption and tubular secretion.	21	1.14	0.36	1.00	0.00
2.1 The kidneys receive about 20% of cardiac output and are supplied by the renal arteries.	20	2.45	0.69	2.00	1.00
2.2 Renal arteries successively divide eventually forming afferent arterioles.	20	2.65	0.88	2.50	1.00
2.2.1 The afferent arteriole delivers blood to the glomerulus where small particles are filtered under pressure through filtration slits comprising fenestrations with overlying podocytes.	20	1.65	0.67	2.00	1.00
2.2.2 Filtration pressure is determined by the sum of systemic hydrostatic pressure, opposing capsular hydrostatic pressure and the oncotic pressure of the glomerulus	20	1.55	0.69	1.00	1.00
2.2.3 The efferent arteriole that leaves the glomerulus then forms low pressure capillary beds that entwine and are closely associated with, the renal tubule of each nephron known as peritubular capillaries.	20	2.30	0.98	2.00	1.00
2.2.4 The vasa recta in the medulla, also formed from efferent arterioles, are closely associated with the juxta medullary nephrons and play an important role in the in establishing a medullary osmotic gradient.	20	2.30	0.66	2.00	1.00
2.3 Filtrate moves from the glomerular capsule into the renal tubule where the filtrate composition is refined, and volume modified via tubular reabsorption and tubular secretion.	21	1.52	0.68	1.00	1.00

2.3.1 Tubular reabsorption (from tubule to blood) and tubular secretion (from blood to tubule) involves passive and active transport mechanisms and the exchange of water and solute particles between tubular cells and surrounding capillaries.	21	1.48	0.60	1.00	1.00
2.3.2 Balance of tubular transport in proximal tubule (bulk transport), Loop of Henle (counter-current exchange), distal tubule and collecting duct (fine tuning) determine the excretion of substances.	21	1.48	0.51	1.00	1.00
2.3.3 Reabsorption of sodium and water in the collecting duct is under the influence of the hormones Aldosterone and Antidiuretic hormone, respectively.	21	1.29	0.46	1.00	1.00
2.3.4 Urine in the collecting ducts flows into the renal pelvis (from the renal pyramids) and then through the ureters into the urinary bladder.	20	1.55	0.60	1.50	1.00
3. Micturition is the term used to describe the emptying of the bladder	20	2.25	1.16	2.00	2.00
3.1 Stretching of the bladder wall, as urine accumulates, initiates the micturition reflex and its emptying.	20	2.15	0.75	2.00	0.75
3.2 Emptying of the bladder involves contraction of the detrusor muscle and relaxation of the internal sphincter.	20	2.20	0.77	2.00	1.00
3.3 Micturition can be delayed through voluntary control of the external sphincter.	20	2.25	0.79	2.00	1.00
4. Between the afferent arteriole and the distal convoluted tubule lies the Juxta glomerular apparatus (JGA) which plays a critical role in regulating renal blood flow, glomerular filtration and systemic blood pressure.	20	1.55	0.60	1.50	1.00
4.1 The JGA comprises the macula densa, extra glomerular mesangial cells and glandular cells.	20	2.05	1.00	2.00	2.00
4.1.1 Glandular cells are specialized smooth muscle cells mainly in the walls of the afferent arterioles that synthesize, store, and secrete the enzyme renin, and is involved in the regulation of systemic blood pressure via the renin-angiotensin-aldosterone mechanism.	20	1.70	0.66	2.00	1.00
4.2 Intrinsic and extrinsic mechanisms provide regulation of Glomerular Filtration Rate (GFR).	21	1.57	0.51	2.00	1.00
4.2.1 Autoregulation (intrinsic) involving tubule glomerular feedback and myogenic reflexes enables constant renal blood flow and GFR.	21	1.90	0.70	2.00	1.00
4.2.2 Extrinsic hormonal and neural input to the kidney maintains GFR.	21	2.00	0.71	2.00	1.00
5. The kidney is critically important in red blood production in the adult.	21	1.57	0.60	2.00	1.00
5.1 The kidney responds to chronic low levels of circulating blood oxygen by secreting Erythropoietin (EPO).	20	1.65	0.67	2.00	1.00
5.1.1 EPO is produced primarily by interstitial fibroblasts in the kidney in the adult and to a lesser extent hepatocytes. The liver in the main site of EPO production in the fetal and perinatal periods.	20	3.10	0.91	3.00	1.75

5.1.2 EPO is secreted into the blood circulatory system and targets erythroid progenitor cells in the bone marrow to stimulate red blood cell production (erythropoiesis) and acts to protect circulating red blood cells from destruction.	20	2.35	0.99	2.00	1.00

Themes and Subthemes	**n**	**Mean**	**SD**	**Median**	**IQR**
1.Comprises kidneys, ureters, a urinary bladder and a urethra	20	4.95	0.22	5.00	0.00
1.1 The kidney is structurally and functionally divided into a cortex and a medulla	20	4.65	0.59	5.00	1.00
1.2 Nephrons are the functional units of the kidney and each kidney comprises approximately 1 million nephrons.	20	4.60	0.50	5.00	1.00
1.2.1 Nephrons are categorised according to their positioning and structure as cortical or Juxta medullary.	20	4.00	0.73	4.00	0.00
1.2.2 Each nephron consists of a renal corpuscle comprising a glomerulus and a glomerular capsule followed by a renal tubule that is continuous with the glomerular capsule.	20	3.80	0.70	4.00	1.00
1.2.3 The renal tubule from the glomerular capsule extends to the proximal convoluted tubule, the loop of Henle, distal convoluted tubule, and the collecting duct.	20	4.05	0.94	4.00	1.00
1.2.4 The collecting ducts collectively form renal pyramids and urine flows from here into the renal pelvis, ureter and on into the urinary bladder where it is held until micturition.	20	4.10	0.64	4.00	0.75
2. Extracellular composition, volume and pH is maintained by the kidneys through physiological processes of glomerular filtration, tubular reabsorption and tubular secretion.	20	3.15	0.67	3.00	1.00
2.1 The kidneys receive about 20% of cardiac output and are supplied by the renal arteries.	20	4.35	0.67	4.00	1.00
2.2 Renal arteries successively divide eventually forming afferent arterioles.	20	4.20	0.83	4.00	1.75
2.2.1 The afferent arteriole delivers blood to the glomerulus where small particles are filtered under pressure through filtration slits comprising fenestrations with overlying podocytes.	20	3.45	0.83	3.00	1.00
2.2.2 Filtration pressure is determined by the sum of systemic hydrostatic pressure, opposing capsular hydrostatic pressure and the oncotic pressure of the glomerulus	20	2.60	0.94	3.00	1.00
2.2.3 The efferent arteriole that leaves the glomerulus then forms low pressure capillary beds that entwine and are closely associated with, the renal tubule of each nephron known as peritubular capillaries.	20	3.45	0.69	3.00	1.00
2.2.4 The vasa recta in the medulla, also formed from efferent arterioles, are closely associated with the juxta medullary nephrons and play an important role in the in establishing a medullary osmotic gradient.	20	2.65	0.93	3.00	1.00
2.3 Filtrate moves from the glomerular capsule into the renal tubule where the filtrate composition is refined, and volume modified via tubular reabsorption and tubular secretion.	21	3.43	0.87	3.00	1.00

2.3.1 Tubular reabsorption (from tubule to blood) and tubular secretion (from blood to tubule) involves passive and active transport mechanisms and the exchange of water and solute particles between tubular cells and surrounding capillaries.	21	2.76	0.89	3.00	1.50
2.3.2 Balance of tubular transport in proximal tubule (bulk transport), Loop of Henle (counter-current exchange), distal tubule and collecting duct (fine tuning) determine the excretion of substances.	21	2.48	0.75	3.00	1.00
2.3.3 Reabsorption of sodium and water in the collecting duct is under the influence of the hormones Aldosterone and Antidiuretic hormone, respectively.	21	3.19	0.81	3.00	1.00
2.3.4 Urine in the collecting ducts flows into the renal pelvis (from the renal pyramids) and then through the ureters into the urinary bladder.	20	4.35	0.75	4.50	1.00
3. Micturition is the term used to describe the emptying of the bladder	20	4.85	0.37	5.00	0.00
3.1 Stretching of the bladder wall, as urine accumulates, initiates the micturition reflex and its emptying.	20	4.05	0.83	4.00	2.00
3.2 Emptying of the bladder involves contraction of the detrusor muscle and relaxation of the internal sphincter.	20	3.85	0.75	4.00	0.75
3.3 Micturition can be delayed through voluntary control of the external sphincter.	20	3.90	0.79	4.00	0.75
4. Between the afferent arteriole and the distal convoluted tubule lies the Juxta glomerular apparatus (JGA) which plays a critical role in regulating renal blood flow, glomerular filtration and systemic blood pressure.	20	2.95	0.76	3.00	0.00
4.1 The JGA comprises the macula densa, extra glomerular mesangial cells and glandular cells.	20	3.40	0.94	3.00	1.00
4.1.1 Glandular cells are specialized smooth muscle cells mainly in the walls of the afferent arterioles that synthesize, store, and secrete the enzyme renin, and is involved in the regulation of systemic blood pressure via the renin-angiotensin-aldosterone mechanism.	20	2.75	1.02	3.00	2.00
4.2 Intrinsic and extrinsic mechanisms provide regulation of Glomerular Filtration Rate (GFR).	21	2.86	1.01	3.00	1.00
4.2.1 Autoregulation (intrinsic) involving tubule glomerular feedback and myogenic reflexes enables constant renal blood flow and GFR.	21	2.67	0.86	3.00	1.00
4.2.2 Extrinsic hormonal and neural input to the kidney maintains GFR.	21	2.90	0.94	3.00	1.50
5. The kidney is critically important in red blood production in the adult.	21	4.24	0.70	4.00	1.00
5.1 The kidney responds to chronic low levels of circulating blood oxygen by secreting Erythropoietin (EPO).	20	3.95	0.60	4.00	0.00
5.1.1 EPO is produced primarily by interstitial fibroblasts in the kidney in the adult and to a lesser extent hepatocytes. The liver in the main site of EPO production in the fetal and perinatal periods.	20	3.40	0.68	3.50	1.00

5.1.2 EPO is secreted into the blood circulatory system and targets erythroid progenitor cells in the bone marrow to stimulate red blood cell production (erythropoiesis) and acts to protect circulating red blood cells from destruction.	20	3.30	0.73	3.00	1.00

Supportive of unpacking	*“Good summary”*
	“Clear and well set-out format. Great work!”
	“It's easier to develop a core concept when the topic is localized/specific, rather than generalized. I liked this CC.”
Suggested improvements	*“Very well appreciated and comprehensive work! I'd suggest though to keep the concepts widely applicable to different systems by crafting the themes to represent general concepts (even if applied best to the renal system). I think this could make it easier to follow it as a template for the other systems”*
	“This is one of the most challenging CC to unpack and the group have done a good job of collating the key aspects of the renal system. My concern is that this isn't what I think of when I think of structure function in a renal sense. I would be wanting my students to explicitly link structure and function in different contexts. For example, the twisting of the nephron and the proximity of the DCT and afferent arteriole as a structural feature that enables paracrine signalling and communication between different regions of the nephron. … This core concept could be improved by another block where key structure function relationships are made more explicit for students.”
	“Minor point that there's nothing here about the role of the kidneys in the activation of Vit D. Might one of the headings be "The kidney as an endocrine organ" - The kidney has multiple endocrine roles; it secretes various hormones and humoral factors: in addition to EPO there are also the hormones of the renin-angiotensin system (RAS) and 1,25 dihydroxy vitamin D3.”
	“I admire the way the renal system has been broken down and explained here with the structure and functional units. This is a big job to do a similar approach for all organ systems. I had thought the Structure Function CC would be more generic, rather than a broader organ by organ breakdown.”