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OSMOSIS AND OSMOTIC PHENOMENA. CONCEPTUAL ANALYSIS AND DIDACTIC MODEL IN PHYSIOLOGY TEACHING

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Abstract. Osmosis and osmotic phenomena are key topics in physiology courses. The quality of their presentation has a significant impact on the effectiveness of the entire physiology teaching process. Despite the importance of the osmotic topic in physiology curricula, there is still no unified, comprehensive and scientifically relevant approach to its presentation among teachers, textbook authors and experts. Consequently, different conceptual frameworks with varying structures and content are employed in teaching, which are often incompatible and contradictory. Therefore, it is reasonable to expect teaching processes based on different conceptual frameworks to be effective to varying degrees. This article presents a logical and conceptual analysis of the osmosis topic in contemporary physiology courses. To address the issues identified and optimise the learning process, a didactic model has been developed to meet the educational needs of medical students and future sports and physical education specialists.

Keywords: human physiology; teaching physiology; medical education; sport education; content analysis; osmotic concepts

1. Introduction

Defining features of modern physiology are its integrative nature and dynamic development (Raychev, 2024). These characteristics also shape the nature of physiology as an academic discipline. It is widely regarded as one of the most challenging subjects in the training of future physicians, and is a leading cause of students dropping out of medical education (Michael, 2007; Slominski et al., 2019).

In an age driven by scientific and technological progress, as well as the social changes these advances provoke, the educational needs of target audiences are also proving to be dynamic. In such an environment, optimising the learning process in many academic disciplines, particularly physiology, requires an approach that combines scientific relevance, the educational needs of learners, and the effectiveness of teaching technology. In physiology education, faculty must identify and emphasise in teaching process fundamental and critical concepts (Michael et al., 2009; Michael & McFarland, 2020; Model, 2000), which appear in various forms throughout the curriculum.

Osmosis and related phenomena are critical and fundamental concepts in physiology, essentially linked to cells, cell membranes, substance transport and homeostasis (Michael et al., 2009; Michael & McFarland, 2020; Model, 2000). The importance of this topic is also evident from its regular coverage at the beginning of textbooks and in the opening lectures of university physiology courses. The topic is characterised by a number of highly specific terms and concepts (e.g. osmolarity, osmotic pressure and semipermeable membrane), which must be precisely defined and interrelated. Together, these terms and concepts can be used to develop a fully integrated, precisely balanced and logically coherent conceptual system. Osmosis and related phenomena and concepts form part of virtually all modern physiology courses for medical students, sports specialists, and students of various biological disciplines. Given this, it is reasonable to expect that the teaching of osmosis in physiology will follow well-established, effective and relatively unified schemes and algorithms. However, the contemporary textbooks reveal widespread discrepancies and incompatible (even contradictory) approaches to defining and using basic concepts and terms, as well as designing the overall conceptual structure of the subject matter devoted to osmosis and related phenomena. Concepts such as 'osmosis', 'osmolarity', 'osmotic concentration' and 'tonicity' are particularly problematic in this regard. A demonstrative example of this is the definition of osmosis. While some authors and faculty consider it to be a type of diffusion (Fox & Rompolski, 2022; Hall & Hall, 2021), others consider osmosis to be an independent process on the same level as diffusion (Boron & Boulpaep, 2017; Silverthorn., 2019). A similar situation exists with the concept of 'osmolarity'. Some authors define it as a measure of the total number of particles (Widmaier et al., 2019; Vitanova & Gurchev, 2020), while others define it as a measure of the number of osmotically active particles (Boron & Boulpaep, 2017; Hall & Hall, 2021). This diversity of incompatible approaches to the topic among university lecturers and authors of educational literature indicates conceptual confusion surrounding it. This naturally leads to students experiencing difficulties in mastering this important physiology subject (Cheng & Durairajanayagam, 2012). Clearly, not all of these approaches are equally scientifically relevant, logically coherent or effective for teaching purposes. Therefore, in planning and conducting the learning process, contemporary authors, teachers, and physiology education experts must develop optimal didactic solutions in teaching osmosis and osmotic phenomena.

2. Methods

A critical content analysis of contemporary textbooks on physiology is used to identify problem areas in the teaching of osmosis and osmotic phenomena. The analysis covers definitions of relevant concepts and their interrelationships, as well as terminology and the subject's positioning within the curriculum. The scientific reliability and relevance of the educational content, and the logical coherence and structure of its presentation, are also considered.

The analysis is based on educational literature published after 2010 intended mainly for training healthcare personnel, particularly medical students (Alipov, 2013; Barrett et al., 2019; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Brandes et al., 2019; Conti, 2020; Costanzo, 2018; Fox & Rompolski, 2022; Derrickson, 2017; Hall & Hall, 2021; Khurana & Khurana, 2022; Kibble, 2020; Koeppen & Stanton, 2024; Mulroney

& Myers, 2015; Pal, 2017; Pape et al., 2023; Raff & LevItzky, 2011; Rhoades & Bell, 2018; Sembulingam & Sembulingam, 2012; Sherwood & Ward, 2019; Silbernagl & Despopoulos, 2015; Silverthorn, 2019; Sircar, 2014; Stanfield, 2017; Widmaier et al., 2019; Vitanova & Gurchev, 2020; Yankov, 2013). Textbooks on physiology intended for the training of sports professionals are also included (Draper et al., 2024; Katch et al., 2011; Kenney et al., 2012; Mihaylov, 2017; Plowman & Smith, 2014; Powers & Howley, 2018). To select more established and authoritative sources (33 in total), the sample includes educational and supplementary literature that has undergone two or more editions. The sources studied are primarily in English, but also are included textbooks in German (Brandes et al., 2019; Pape et al., 2023), Bulgarian (Mihaylov, 2017; Vitanova & Gurchev, 2020; Yankov, 2013), Russian (Alipov, 2013) and Italian (Conti, 2020).

The principles underlying the design of the didactic model are scientific accuracy and relevance, logical coherence of terminology and concepts, and educational needs of the audience.The presence of analysed terms and concepts in educational content and the variety of their definitions and presentations re assessed on a frequency scaling system of five levels. This is based on the percentage inclusion of analysed terms, concepts and definitions in the selected source sample. The levels of the scale are defined as follows: (1) completely absent or found in fewer than 5% of sources, (2) rare (found in 5 – 24% of sources), (3) frequent (found in 25 – 66% of sources), (4) widely accepted (found in 67 – 95% of sources), and (5) generally accepted (found in more than 95% of sources).

3. Results

3.1. Osmosis and osmotic phenomena as a topic in physiology courses

3.1.1. Positioning of the topic

Osmosis and osmotic phenomena lie at the core of many physiological processes. Consequently, contemporary university teachers and authors of teaching literature introduce them in the opening lectures of courses and in the introductory sections of physiology textbooks. Exceptions to this are very rare (Alipov, 2013; Conti, 2020). However, certain concepts and terms related to osmosis are frequently introduced in sections other than those devoted to it. For example, terms such as ‘aquaporin’, ‘oncotic pressure’ and ‘tonicity’ are commonly introduced under headings about blood, urine formation and water-salt balance.

3.1.2. Osmotic concepts

Introducing osmotic content into physiology courses necessitates the use of numerous highly specific and interrelated terms and concepts rooted in non-biological sciences such as physics and chemistry. However, their application in the context of physiology necessitates consideration of specific characteristics of living cells (e.g. membrane structure and properties) and the organism as a whole. Key terms and concepts related to osmosis in physiology courses include osmol, osmotic concentration, semipermeable membrane, osmosis, aquaporin, tonicity, osmotic pressure, oncotic pressure, osmotic gradient, osmotic equilibrium and the Gibbs–Donnan effect. This analysis focuses on some of the most problematic terms and concepts frequently included in the curriculum (see Table 1).

Table 1. Most frequently used terms and concepts related to osmosis and osmotic phenomena in human physiology textbooks. Summary data is presented from 33 physiology textbooks published after 2010

No	Term/concept	Sources referring the term/concept	% of the sample	Rating of the presence in the sample
1	Osmoticity	32	97	generally accepted
2	Osmotic pressure	29	88	widely accepted
3	Tonicity	28	85	widely accepted
4	Osmol	25	76	widely accepted
5	Osmosis	25	76	widely accepted
6	Aquaporins	24	73	widely accepted
7	Colloid-osmotic and oncotic pressure	23	70	widely accepted
8	Osmotic balance	17	52	frequent
9	Semipermeable membrane	15	46	frequent
10	Effect of Gibbs-Donnan	15	46	frequent
11	Solvent drag	11	33	frequent
12	Reflection coefficient	10	30	frequent

Osmotic concentration (osmoticity). This is a widely accepted concept in contemporary physiology textbooks. It is presented in almost all of the textbooks in the sample (97% of the analysed sources). However, significant differences are observed in its definition. The majority of authors (17 sources, accounting for 52% of the sample) define it as the total concentration of dissolved particles (Alipov, 2013; Conti, 2020; Derrickson, 2017; Fox & Rompolski, 2022; Kenney et al., 2012; Kibble, 2020; Koeppen & Stanton, 2024; Mihaylov, 2017; Mulroney & Myers, 2015; Raff & Levitzky, 2011; Rhoades & Bell, 2018; Sherwood & Ward, 2019; Silverthorn, 2019; Stanfield, 2017; Vitanova & Gurchev, 2020; Widmaier et al., 2019; Yankov, 2013). In this way, they decouple osmotic concentration from its historical association with osmosis, instead defining it as a colligative property of solutions. In light of this, the authors' decision to include the freezing point depression method for determining osmotic concentration in the curriculum is both logical and pedagogically sound (Fox & Rompolski, 2022; Raff & Levitzky, 2011; Rhoades & Bell, 2018).

According to another common definition, osmotic concentration reflects only the concentration of osmotically active particles (i.e., particles that the membrane is impermeable to) (Barrett et al., 2019; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Costanzo, 2018; Hall & Hall, 2021; Khurana & Khurana, 2022; Pal, 2017; Pape et al., 2023; Sembulingam & Sembulingam, 2012; Silbernagl & Despopoulos, 2015; Sircar, 2014). Some authors also state that osmotic concentration is a measure of a solution's ability to generate osmotic pressure (Sembulingam & Sembulingam, 2012). Therefore, the osmotic concentration of a solution is implicitly presented as a function of the properties of the semipermeable membrane. This implies that solutions with the same qualitative and quantitative composition can have many different osmotic concentrations.

There is an obvious logical contradiction between the concept of osmotic pressure as a colligative property of a solution and the concept of osmotic pressure as a property based on osmotically active particles (Barrett et al., 2019; Pal, 2017; Sircar, 2014). A similar contradiction is observed in another textbook (Kibble, 2020, p. 8), where osmolar concentration is defined as "...an expression of the osmotic strength of a solution and is the total solute concentration."

In physiology courses, osmotic concentration is given as either osmolarity (osm/L) or osmolality (osm/kg). Of the 33 sources in the sample, 21 (making up about 64%) include both units of measurement in their texts (e.g. Alipov, 2013; Barrett et al., 2019; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Conti, 2020; Costanzo, 2018; Derrickson, 2017; Hall & Hall, 2021; Kenney et al., 2012; Koeppen & Stanton, 2024; Pal 2017; Pape et al., 2023; Plowman & Smith, 2014; Raff & Levitzky, 2011; Sembulingam & Sembulingam, 2012; Sherwood & Ward, 2019; Silbernagl & Despopoulos, 2015; Silverthorn, 2019; Sircar, 2014; Vitanova & Gurchev, 2020; Yankov, 2013), which is consistent with the educational needs of medical students. In rare cases (six sources, or 18% of the sample), the authors only present one unit of measurement for osmotic pressure: osmolarity (Kibble, 2020; Mihaylov, 2017; Stanfield, 2017; Widmaier et al., 2019), or osmolality (Fox & Rompolski, 2022; Katch et al., 2011).

From a logical and didactic perspective, the concept of osmotic concentration is better introduced in a general section alongside osmosis and related concepts, rather than as part of specific sections such as body fluids, water-salt balance, or urine formation (Rhoades & Bell, 2018; Pape et al., 2023; Sembulingam & Sembulingam, 2012). The rationale behind this is that osmoticity provides the basis for defining the concepts of osmotic balance, osmosis and osmolyte. Therefore, in the teaching process, osmoticity can serve as a connecting link in forming a coherent system of concepts.

For a meaningful definition of osmotic concentration, the concept of osmol must be precisely and consistently formulated. However, many textbook authors do not clearly distinguish between osmol and mol, which may give learners the impression that these terms are almost synonymous (Alipov, 2013; Fox & Rompolski, 2022; Sherwood & Ward, 2019; Widmaier et al., 2019). For example, Fox's textbook states: 'The expression for the total molality of a solution is osmolality (Osm),' while Widmaier's states: 'One osmol is equal to 1 mol of solute particles.' Notably, in 17 sources (approximately 52% of the sample), authors use the term 'osmotic concentration' without defining 'osmol' as both a concept and a unit of measurement (e.g. Bijlani & Manjunatha, 2011; Brandes et al., 2019; Conti, 2020; Derrickson, 2017; Fox & Rompolski, 2022; Katch et al., 2011; Kenney et al., 2012; Kibble, 2020; Mihaylov, 2017; Mulroney & Myers, 2015; Pape et al., 2023; Plowman & Smith, 2014; Powers & Howley, 2018; Raff & Levitzky, 2011; Sherwood & Ward, 2019; Silbernagl & Despopoulos, 2015; Silverthorn., 2019).

Osmotic balance (equilibrium). Osmotic balance in physiology courses (Barrett et al., 2019; Boron & Boulpaep, 2017; Costanzo, 2018; Derrickson, 2017; Hall & Hall, 2021; Sembulingam & Sembulingam, 2012; Khurana & Khurana, 2022; Koeppen & Stanton, 2024; Pal, 2017; Raff & Levitzky, 2011; Rhoades & Bell, 2018; Sherwood & Ward, 2019; Silbernagl et al., 2015; Silverthorn., 2019; Sircar, 2014; Stanfield, 2017; Widmaier et al., 2019) is frequently mentioned (17 sources, 52% of the sample). It is commonly used as a term and rarely (15% of the sample) defined as a concept (Derrickson, 2017; Hall &

Hall, 2021; Rhoades & Bell, 2018; Silverthorn, 2019; Stanfield, 2017). Some authors consider osmotic balance outside the topic of osmosis (Rhoades & Bell, 2018). In regard to cells in the body, it is defined as a state in which the concentrations of particles to which semipermeable membrane is impermeable are equal on both sides and osmosis does not occur (Derrickson, 2017).

Semipermeable membrane. This concept is frequently included in textbooks of physiology, appearing in 15 sources (46% of the sample). The subject appears either as a term (Barrett et al., 2019; Boron & Boulpaep, 2017; Costanzo, 2018; Hall & Hall, 2021) or as a defined concept (Kibble, 2020; Khurana & Khurana, 2022; Koeppen & Stanton, 2024; Mihaylov, 2017; Mulroney & Myers, 2015; Pal, 2017; Pape et al., 2023; Sembulingam & Sembulingam, 2012; Sircar, 2014; Stanfield, 2017; Widmaier et al., 2019). The semipermeable membrane is defined as a membrane that is permeable to solvent particles – in living organisms, this is water – and impermeable to dissolved particles (Kibble, 2020; Khurana & Khurana, 2022; Koeppen & Stanton, 2024; Mihaylov, 2017; Mulroney & Myers, 2015; Pal, 2017; Pape et al., 2023; Sembulingam & Sembulingam, 2012; Stanfield, 2017; Widmaier et al., 2019). According to a more concise definition, a semipermeable membrane is impermeable to dissolved particles (Sircar, 2014). However, some authors do not distinguish between a selectively permeable membrane and its specific subtype, the semipermeable membrane. Some authors use these terms interchangeably (Barrett et al., 2019; Hall & Hall, 2021, pp. 57–58; Mulroney & Myers, 2015, p. 4), while others only use the term 'selectivly permeabe membrane' (Alipov, 2013; Bijlani & Manjunatha, 2011; Derrickson, 2017; Rhoades & Bell, 2018).

Reflection coefficient (σ). The reflection coefficient is often (10 sources, 30% of the sample) introduced as a quantitative characteristic of the properties of the semi-permeable membrane (Boron & Boulpaep, 2017; Costanzo, 2018; Kibble, 2020; Koepen et al., 2024; Mulroney & Myers, 2015; Pape et al., 2023; Raff & Levitzky, 2011; Silbernagl & Despopoulos, 2015; Sircar, 2014). Sometimes its value ($\sigma = 1$) is used to define the concept of a semipermeable membrane (Pape et al., 2023, p. 1046; Silbernagl & Despopoulos, 2015, p. 399; Sircar, 2014, p. 20). Some authors prefer to define the reflection coefficient as a measure of the ability of dissolved particles to pass through the membrane (Raff & Levitzky, 2011). Interestingly, the reflection coefficient is sometimes present in educational content while the semipermeable membrane is not defined as a concept at all (Costanzo, 2018) or even mentioned (Raff & Levitzky, 2011). Some authors introduce the reflection coefficient outside the topic of osmosis (Mulroney & Myers, 2015).

Aquaporins. The introduction of aquaporins in the curriculum of physiology courses (Alipov, 2013; Barrett et al., 2019; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Brandes et al., 2019; Conti, 2020; Costanzo, 2018; Derrickson, 2017; Fox & Rompolski, 2022; Hall & Hall, 2021; Khurana & Khurana, 2022; Kibble, 2020; Pal, 2017; Pape et al., 2023; Raff & Levitzky, 2011; Rhoades & Bell, 2018; Sembulingam & Sembulingam, 2012; Silbernagl & Despopoulos, 2015; Silverthorn, 2019; Sherwood & Ward, 2019; Sircar, 2014; Stanfield, 2017; Vitanova & Gurchev, 2020; Widmaier et al., 2019; Yankov, 2013) is widely accepted (24 sources, 74% of the sample). However, they are often (12 sources, 36% of the sample) introduced as a concept or term in reference to more specific physiological processes and phenomena such as urine formation and water-salt balance,

in sections that do not specifically address osmosis (Alipov, 2013; Barrett et al., 2019; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Conti, 2020; Costanzo, 2018; Khurana & Khurana, 2022; Kibble, 2020; Pal, 2017; Pape et al., 2023; Sembulingam & Sembulingam, 2012; Sircar, 2014).

Some authors define the passage of water molecules through aquaporins as diffusion (Stanfield, 2017, p. 135) or simple diffusion (Sircar 2014, p. 38).

Osmosis. The presence of osmosis as a term and concept is widely accepted (25 sources, 76% of the sample) in physiology textbooks for medical students (Alipov, 2013; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Brandes et al., 2019; Conti, 2020; Costanzo, 2018; Derrickson, 2017; Fox & Rompolski, 2022; Hall & Hall, 2021; Khurana & Khurana, 2022; Kibble, 2020; Koeppen & Stanton, 2024; Mihaylov, 2017; Mulroney & Myers, 2015; Pal, 2017; Raff & Levitzky, 2011; Rhoades & Bell, 2018; Sembulingam & Sembulingam, 2012; Sherwood & Ward, 2019; Silbernagl & Despopoulos, 2015; Silverthorn, 2019; Sircar, 2014; Stanfield, 2017; Widmaier et al., 2019; Vitanova & Gurchev, 2020; Yankov, 2013). Interestingly, the situation is quite different among authors of sports physiology textbooks, who rarely include osmosis as a term or concept in educational content (Mihaylov, 2017), or only do so fragmentarily and superficially (Draper et al., 2024). An interesting paradox is observed in some of the analysed textbooks (Katch et al., 2011; Pape et al., 2023; Powers & Howley, 2018), in which osmosis is absent as both a term and a concept, yet a significant proportion of related terminology and conceptual tools are presented in the learning content.

Two primary conceptualisations of osmosis emerge from the analysed textbooks. The first, which appears in 15 sources (45% of the sample), defines osmosis as the diffusion of water, meaning that water molecules move passively from a region of higher concentration to one of lower concentration through a semipermeable or selectively permeable membrane. In other words, osmosis is defined as a specific type of diffusion (Barrett et al., 2019; Bijlani & Manjunatha, 2011; Brandes et al., 2019; Derrickson, 2017; Fox & Rompolski, 2022; Hall & Hall, 2021; Khurana & Khurana, 2022; Kibble, 2020; Mihaylov, 2017; Mulroney & Myers, 2015; Raff & Levitzky, 2011; Sherwood & Ward, 2019; Silbernagl & Despopoulos, 2015; Widmaier et al, 2019; Vitanova & Gurchev, 2020). Based on the existence of concentration gradients for water, some authors go so far as to claim that "...the principles of osmosis are the same as those governing the diffusion of solute molecules through a membrane" (Fox & Rompolski, 2022, p. 134) or that "... osmosis is nothing more than diffusion of water down its own concentration gradient across the membrane" (Sherwood & Ward, 2019, p. 39). However, they do not clarify whether Fick's laws of diffusion also apply to osmosis. Other authors who define osmosis as diffusion do not mention the role of the semipermeable membrane (Brandes et al., 2019, p. 30). One of the textbooks in the sample defines osmosis as the diffusion of water. Nevertheless, equations describing diffusion and osmotic flow clearly demonstrate that these processes are distinct and incomparable (Silbernagl & Despopoulos, 2015, p. 24). In another instance, the author equates osmosis with simple diffusion (Derrickson, 2017, p. 137). This group also includes authors who present osmosis as passive flow through a cell or semipermeable membrane based on the water concentration gradient without using the term 'diffusion'. Thus, they implicitly suggest that osmosis is a form of diffusion (Rhoades & Bell, 2018; Stanfield, 2017).

The second primary definition of osmosis is comparatively rare, appearing in only eight sources (24% of the sample). According to this definition, osmosis is the movement of solvent particles (e.g. water) from a solution with a lower concentration of dissolved particles to a solution with a higher concentration, passing through a membrane (Alipov, 2013; Boron & Boulpaep, 2017; Conti, 2020; Costanzo, 2018; Pal, 2017; Silverthorn, 2019; Yankov, 2013). This membrane can be semipermeable (Sircar, 2014) or selectively permeable (e.g. the cell membrane). Some authors controversially define osmosis as a special type of water diffusion (Sembulingam & Sembulingam, 2012, p. 30), pointing out that it flows from a solution with a lower concentration of dissolved substance to a solution with a higher concentration.

Osmosis is also defined as 'the movement of water between cells and their outside environment' (Draper et al., 2024, p. 61). However, this definition overlooks the fact that it is a universal physical phenomenon.

Some authors distinguish between exosmosis and endosmosis (Sembulingam & Sembulingam, 2012, p. 31). From a didactic point of view, this seems like a useful distinction.

An important aspect of osmosis is its driving force. There are many different and contradictory concepts about the latter. For example, physiology textbooks cite the concentration gradient of water (Brandes et al., 2019; Kibble, 2020; Sherwood & Ward, 2019), the osmotic concentration gradient (Boron & Boulpaep, 2017; Bijlani & Manjunatha, 2011; Pape et al., 2023), osmotic pressure (Costanzo, 2018; Koeppen & Stanton, 2024), and the osmotic pressure difference (Raff & Levitzky, 2011; Silverthorn, 2019). Sometimes, authors of the same textbook mention two of these forces simultaneously, e.g. the water concentration gradient and osmotic pressure (Rhoades & Bell, 2018); the water concentration gradient and osmotic concentration gradient (Silbernagl & Despopoulos, 2015, p. 24); or osmotic pressure and osmotic concentration gradient (Bijlani & Manjunatha, 2011, pp. 30, 344). Remarkably, the thermal motion of solvent particles and the thermodynamic activity of water are rarely associated with the driving force of osmosis (Pal, 2017, p. 47).

Osmotic pressure. In contemporary physiology textbooks, it is widely accepted (29 sources, 88% of the sample) introduction of osmotic pressure as a concept (Alipov, 2013; Barrett et al., 2019; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Brandes et al., 2019; Conti, 2020; Costanzo, 2018; Fox & Rompolski, 2022; Derrickson, 2017; Hall & Hall, 2021; Katch et al., 2011; Khurana & Khurana, 2022; Kibble 2020; Koeppen & Stanton, 2024; Mulroney & Myers, 2015; Pal, 2017; Pape et al., 2023; Plowman & Smith, 2014; Raff & Levitzky, 2011; Rhoades & Bell, 2018; Sherwood & Ward, 2019; Silbernagl & Despopoulos, 2015; Sembulingam & Sembulingam, 2012; Silverthorn, 2019; Sircar, 2014; Stanfield, 2017; Widmaier et al., 2019; Vitanova & Gurchev, 2020; Yankov, 2013). Its use as a term alone (without definition) is rare (Boron & Boulpaep, 2017; Katch et al., 2011; Plowman & Smith, 2014).

Osmotic pressure is often defined as the pressure needed to stop osmosis (Barrett et al., 2019; Costanzo, 2018; Derrickson, 2017; Fox & Rompolski, 2022; Hall & Hall, 2021; Khurana & Khurana, 2022; Kibble, 2020; Koeppen & Stanton, 2024; Pal, 2017; Rhoades & Bell, 2018; Silverthorn, 2019; Sircar, 2014; Widmaier et al., 2019; Vitanova & Gurchev, 2020). Some authors use the term 'osmotic forces' to describe what osmotic pressure opposes, but do not clarify their nature (Vitanova & Gurchev, 2020, p. 22). The

following definition is similar: ‘Osmotic pressure is the mechanical pressure needed to produce a flow of water equal to and in the opposite direction to the osmotic flow produced by a water concentration gradient’ (Raff & Levitzky, 2011, p. 28). Osmotic pressure is also defined as ‘the tendency of water to move into a more concentrated solution’ (Draper et al., 2024, p. 207).

Some authors present osmotic pressure as counteracting osmosis, which arises from the dilution of a more concentrated solution (Sembulingam & Sembulingam, 2012, p. 30). One physiology textbook states: ‘Normally, the osmotic pressure prevents further movement of water or other solvent during osmosis’ (Sembulingam & Sembulingam, 2012, p. 30). There are also authors who define osmotic pressure as being caused by osmosis and opposing it (Brandes et al., 2019, p. 30).

Vant Hoff’s equation is frequently used to explain osmotic pressure (10 sources, 30% of the sample) (Brandes et al., 2019; Conti, 2020; Costanzo, 2018; Pape et al., 2023; Raff & Levitzky, 2011; Silbernagl & Despopoulos, 2015; Sircar, 2014; Stanfield, 2017; Vitanova & Gurchev, 2020; Yankov, 2013). Some authors state that osmotic pressure depends on the osmotic concentration of solutions (Conti, 2020; Pape et al., 2023; Stanfield, 2017, p. 143).

A striking feature of contemporary physiology textbooks is that osmotic pressure is only explained as the pressure that causes osmosis in three out of the entire sample analysed (Alipov, 2013, p. 171; Bijlani & Manjunatha, 2011, p. 31; Kenney et al., 2012, p. 584). Osmotic pressure does not stop osmosis; rather, it drives it. For example, it is osmotic pressure that causes the hemolysis of red blood cells when they are placed in a hypotonic solution. Some authors (Costanzo, 2018, p. 12) present an obvious contradiction between osmotic pressure as a factor that stops osmosis and as a factor that drives it. In this regard, the following confusing text is illustrative: “Osmosis occurs when osmotic pressure is present. Osmotic pressure is equivalent to the hydrostatic pressure necessary to prevent movement of fluid through a semipermeable membrane by osmosis.” (Mulroney & Myers, 2015, p. 7).

With regard to teaching colloid-osmotic pressure as a specific form of osmotic pressure, it is an interesting idea to categorise the latter as a crystalloid and a colloid (Bijlani & Manjunatha, 2011, p. 172).

Tonicity of solutions. The inclusion of tonicity of solutions in the curriculum of physiology courses (28 sources, 85% of the sample) as a term or concept is widely accepted (Alipov, 2013; Barrett et al., 2019; Bijlani & Manjunatha, 2011; Boron & Boulpaep, 2017; Brandes et al., 2019; Conti, 2020; Costanzo, 2018; Fox & Rompolski, 2022; Derrickson, 2017; Hall & Hall, 2021; Khurana & Khurana, 2022; Kibble, 2020; Koeppen & Stanton, 2024; Mihaylov, 2017; Mulroney & Myers, 2015; Pal, 2017; Pape et al., 2023; Raff & Levitzky, 2011; Rhoades & Bell, 2018; Sherwood & Ward, 2019; Silbernagl & Despopoulos, 2015; Sembulingam & Sembulingam, 2012; Silverthorn, 2019; Sircar, 2014; Stanfield, 2017; Widmaier et al., 2019; Vitanova & Gurchev, 2020; Yankov, 2013). This mainly applies to courses aimed at medical students.

In physiology textbooks, the tonicity of a solution is frequently (14 sources, 42% of the sample) defined based on its effect on the volume of living cells, respectively on the osmotic movement of water. According to this criterion, the solution can be hypertonic, isotonic, or hypotonic, with a distinction usually made between tonicity and osmoticity

(Alipov, 2013; Conti, 2020; Derrickson, 2017; Fox & Rompolski, 2022; Hall & Hall, 2021; Khurana & Khurana, 2022; Koeppen & Stanton, 2024; Rhoades & Bell, 2018; Raff & Levitzky, 2011; Sherwood & Ward 2019; Silverthorn, 2019; Sircar, 2014; Stanfield, 2017; Widmaier et al., 2019). An important aspect of the conceptualisation of tonicity is establishing an explicit link with the properties of the semipermeable membrane (Derrickson, 2017; Fox & Rompolski, 2022; Koeppen & Stanton, 2024; Rhoades & Bell, 2018; Raff & Levitzky, 2011; Sembulingam & Sembulingam, 2012; Sherwood & Ward, 2019). This emphasises that tonicity is not solely dependent on the composition of the solution, as some authors claim (Silverthorn, 2019, p. 126). As one author correctly notes, the complexity of biological membranes and the multicomponent composition of body fluids make it practically impossible to accurately predict tonicity based on osmotic concentration (Sircar, 2014, p. 22).

In rare cases (9%), tonicity is also defined as the osmoticity of solutions relative to the osmotic concentration of blood plasma. However, this ignores its biological nature, i.e. that it is also a function of the properties of complex biological membranes (Barrett et al., 2019; Khurana & Khurana, 2022; Pal, 2017).

Some textbooks define tonicity solely in terms of the concentration of particles that the cell membrane is impermeable to (Derrickson, 2017; Rhoades & Bell, 2018; Sherwood & Ward, 2019; Silverthorn, 2019; Widmaier et al., 2019), which can create osmotic pressure (Pape et al., 2023). Similarly, tonicity is defined as the effective osmoticity of the solution (Boron & Boulpaep, 2017; Kibble, 2020; Sembulingam & Sembulingam, 2012). However, all of these definitions are incompatible with the classic example of erythrocytes placed in an isosmotic urea solution (300 mosm/l), which acts hypotonically and causes haemolysis (see Stanfield 2017, p. 143, for example).

One interesting approach is deriving and defining tonicity based on the reflection coefficient of the semipermeable membrane (Conti, 2020, p. 429). Some authors associate the tonicity of solutions to their ability to create an osmotic gradient, without, however, defining the latter as a concept (Vitanova & Gurchev, 2020, p. 23).

3.2. Didactic model for integrating osmosis and related concepts into physiology education

Basic concepts in the model. The didactic model includes the following basic terms and concepts: osmol, osmoticity (osmolarity and osmolality), semipermeable membrane, aquaporins, osmosis, reflection coefficient, osmolytes, osmotic pressure, colloid-osmotic and oncotic pressure, and tonicity of solutions.

Algorithm of the model. The didactic model can be implemented in the steps of the linear algorithm presented below.

Step 1: Introduction to the concept of 'osmol'. This step could start with a review of the mole, the unit of measurement for the amount of substance. This enables students to compare the mole and the osmol, and to understand their similarities and differences. Osmol is defined as a quantitative measure that reflects the ratio of a given total number of particles to Avogadro's number (N_A).

Step 2: Introduction to the concept of the osmoticity of solutions. This step may begin with a review of molar and molal concentration. Building on this, learners are introduced to the two main ways of expressing osmotic concentration: osmolarity and osmolality. Osmoticity is presented as a measure of the total concentration of solutions,

taking into account all dissolved particles regardless of their nature. Students learn that osmoticity can also be used to compare the osmotic concentrations of two solutions. The terms 'hypo-, iso- and hyperosmotic solutions' are then introduced.

Step 3: Gaining skills to calculate the osmotic concentration of solutions. Students learn the formulas for calculating the osmotic concentration of single- and multi-component solutions. They develop the ability to apply these formulas and interpret the results by solving specific problems.

Step 4: Developing the ability to quickly estimate the osmoticity of blood plasma. In this step, the following formula for evaluating blood plasma osmoticity should be presented, as it is widely used in physiology and clinical practice:

$CO = 2[NaCl]pl + [Urea]pl + [Glucose]pl$

Specific tasks with values close to physiological ones are solved. The results obtained are then discussed and analysed. The formula and its parameters can be discussed.

Step 5: Introduction to the concept of osmotic balance. Osmotic balance is defined as maintaining an equal osmotic concentration of solutions on either side of the cell membrane, and more generally as maintaining iso-osmoticity between the body's different compartments. It must be explained to the audience that an equal osmotic concentration does not imply an equal quantitative or qualitative composition of the solutions on either side of the cell membrane. Illustrative examples include comparisons between the concentrations of sodium, potassium, chlorine ions and other particles in the intracellular and extracellular spaces. Osmosis can be cited as the main mechanism ensuring osmotic equilibrium in the body.

Step 6: Introduction of the concept of a 'semipermeable membrane'. Semipermeable membrane is defined as a membrane that is permeable only to solvent particles, such as water. It is important to distinguish between an ideal semipermeable membrane and a real one. This can be achieved by considering the reflection coefficient and its values. At this stage, aquaporins can be introduced as a key factor in ensuring the semi-permeability of cell membranes.

Step 7: Defining the concept of osmosis. From a physiological perspective, osmosis is defined as the movement of water molecules through a semipermeable membrane from a hypoosmotic solution to a hyperosmotic solution, i.e. from a solution with a lower osmotic concentration to a solution with a higher concentration. Diagrams are helpful for illustrating a model system based on a living cell in which osmosis occurs. The driving force of osmosis is thermal particle motion, also referred to as osmotic pressure.

Step 8: Introduction to the concept of osmotic pressure. Osmotic pressure is defined as the pressure that causes water to flow by osmosis. It is measured by the magnitude of the hydrostatic pressure required to stop this flow; however, the two are not identical. At this stage of the teaching process, it is advisable to use the van 't Hoff equation to analyse the parameters and their contribution to the osmotic pressure value.

Step 9: This is an introduction to the concepts of 'osmotic activity' and 'osmolyte'. An osmotically active particle is defined as a particle that a semipermeable membrane is impermeable to. These particles, expressed in osmoles, are called osmolytes.

Step 10: Forming the concept of colloid-osmotic and oncotic pressure. Colloid-osmotic and oncotic pressure can be presented as specific types of osmotic pressure. Oncotic pressure can be defined as a type of colloid-osmotic pressure relating to blood

plasma in the capillaries. The capillary endothelium is highlighted as a specific type of semipermeable membrane that is permeable to almost all components of blood plasma, except for large protein molecules.

Step 11: Introduction to the tonicity of solutions. Tonicity is defined as the biological property of solutions that determines their ability to alter cell volume. The terms hypotonic, isotonic and hypertonic solutions are introduced. It is important to be emphasised the difference between osmoticity and tonicity, based on the fact that real biological membranes are permeable to many substances other than water and are therefore not ideal semipermeable membranes. An example that illustrates this is the hemolysis of erythrocytes when they are placed in an iso-osmotic urea solution (300 mosm/L).

Step 12: Additional concepts and topics. Depending on the educational needs of the audience, the teaching content can be expanded to include additional topics and concepts. These can be within the topic of 'Osmosis' or in other related sections (e.g., water-salt balance). Examples include the Gibbs-Donnan effect and the role of the sodium-potassium pump in maintaining osmoticity of the cells.

4. Discussion and conclusion

An analysis of the educational content of contemporary physiology courses reveals significant discrepancies and contradictions in the conceptual presentation of osmosis and related terms and concepts. These discrepancies can be identified in three areas: the definition of concepts; the context in which terms and concepts are introduced and presented; and the general logical structure of the system of interrelated concepts.

A common issue in the introduction and application of key concepts is the absence of explicit definitions in the texts, with the terms merely being referenced. This issue affects not only marginal, less significant concepts, but also fundamental and critical ones, such as 'osmol', 'osmosis' and 'semipermeable membrane'. In this context, the concept of 'osmol' is a particularly notable example. In educational literature, it often appears only as a term (in 52% of analysed sources). Another significant issue is inaccurate or contradictory definitions of concepts. The concepts of osmolality, osmotic concentration, semipermeable membrane and osmotic pressure are illustrative of this problem. Such problems reduce the effectiveness of the teaching process by making it impossible to present learners with a comprehensive, optimally hierarchical, logically consistent and scientifically relevant system of concepts. Similar difficulties arise when key terms and concepts related to osmosis are not presented under a specific section heading, but instead introduced in isolation within topics such as water-salt balance, urine formation or digestion.

Presented didactic model is developed on the basis of the implemented content analysis of modern physiology textbooks and proven teaching practices followed by logical synthesis. The model addresses structural, logical, and content-related issues concerning osmosis and related concepts in physiology courses. Key emphasis is placed on defining the concepts and their interconnections in a coherent way. The algorithm underlying the model is based on these emphases, providing a coherent, logical framework for presenting the topic of osmosis and related phenomena. This didactic model has been specifically developed for the training of future physicians, sports specialists and other professionals with various biological profiles, for whom physiology is a core discipline. It can be modified according to the educational needs and prior training of the audience

and integrated in different forms of organisation of the teaching process. The model can be implemented within three to four academic hours, organised into one or more sessions (lectures, seminars, exercises, etc.). The algorithm and conceptual framework of the model may be applicable in the design and development of software systems for electronic and AI-based learning.

REFERENCES

Alipov, N. (2013). *Osnovy meditsinskoy fiziologii* (2nd Ed.). Praktika. [In Russian]

Barrett, K. E., Barman, S. M., Brooks, H. L., & Yuan, J. X.-J. (2019). *Ganong's Review of Medical Physiology* (26th Ed.). McGraw Hill.

Bijlani, R. L., & Manjunatha, S. (2011). *Understanding medical physiology: A textbook for medical students* (4th Ed). Jaypee Brothers Medical Pub.

Boron, W. F., & Boulpaep, E. L. (Eds). (2017). *Medical physiology* (3rd Ed.). Elsevier.

Brandes, R., Lang, F., & Schmidt, R. F. (Eds). (2019). *Physiologie des Menschen: Mit Pathophysiologie* (32. Aufl). Springer.

Cheng, H.-M., & Durairajanayagam, D. (2012). Misconceptions highlighted among medical students in the annual International Intermedical School Physiology Quiz. *Advances in Physiology Education*, *36*(3), 229 – 232. https://doi.org/10.1152/advan.00089.2011.

Conti, F. (Ed.). (2020). *Fisiologia medica: Vol. 2* (3th Ed.). Edi-Ermes. [In Italian]

Costanzo, L. S. (2018). *Physiology* (6th Ed.). Elsevier.

Derrickson, B. H. (2017). *Human physiology*. Wiley.

Draper, N., Williams, C., & Marshall, H. (2024). *Exercise physiology: For health and sports performance* (2nd Ed.). Routledge. https://doi.org/10.4324/9781003109280.

Fox, S. I., & Rompolski, K. (2022). *Human physiology* (16th Ed.). McGraw-Hill.

Hall, J. E., & Hall, M. E. (2021). *Guyton and Hall textbook of medical physiology* (14th Ed.). Elsevier.

Katch, V. L., McArdle, W. D., & Katch, F. I. (2011). *Essentials of exercise physiology* (4th Ed). Wolters Kluwer.

Kenney, W. L., Wilmore, J. H., & Costill, D. L. (2012). *Physiology of sport and exercise* (5th Ed). Human Kinetics.

Khurana, I., & Khurana, A. (2022). *Concise textbook of physiology* (4th Ed.). Elsevier.

Kibble, J. D. (2020). *The big picture physiology: Medical course & step 1 review* (2nd Ed.). McGraw Hill.

Koeppen, B. M., & Stanton, B. A. (Eds). (2024). *Berne & Levy physiology* (8th Ed.). Elsevier.

Michael, J. (2007). What makes physiology hard for students to learn? Results of a faculty survey. *Advances in Physiology Education*, *31*(1), 34 – 40. https://doi.org/10.1152/advan.00057.2006.

Michael, J., & McFarland, J. (2020). Another look at the core concepts of physiology: Revisions and resources. *Advances in Physiology Education*, *44*(4), 752 – 762. https://doi.org/10.1152/advan.00114.2020.

Michael, J., Modell, H., McFarland, J., & Cliff, W. (2009). The "core principles" of physiology: What should students understand? *Advances in Physiology Education*, *33*(1), 10 – 16. https://doi.org/10.1152/advan.90139.2008.

Mihaylov, V. (2017). *Fiziologiya na choveka.* NSA Press. [In Bulgarian]
Modell, H. I. (2000). How to help students understand physiology? Emphasize general models. *Advances in Physiology Education*, *23*(1), S101 – S107. https://doi.org/10.1152/advances.2000.23.1.S101.
Mulroney, S., & Myers, A. (2015). *Netter's Essential Physiology* (2nd Ed). Elsevier.
Pal, G. K. (2017). *Comprehensive textbook of medical physiology*. *Vol. 1*. Jaypee Brothers Medical Pub.
Pape, H.-C., Kurtz, A., & Silbernagl, S. (Eds). (2023). *Physiologie* (10. Aufl.). Thieme.
Plowman, S. A., & Smith, D. L. (2014). *Exercise physiology: For health, fitness, and performance* (4. Ed). Wolters Kluwer.
Powers, S. K., & Howley, E. T. (2018). *Exercise physiology: Theory and application to fitness and performance* (10th Ed.). McGraw-Hill.
Raff, H., & Levitzky, M. G. (2011). *Medical physiology: A systems approach*. McGraw-Hill.
Raychev, P. (2024). *Didakticheski modeli v obuchenieto po fiziologiya: Problemi i alternativi* University press „Sv. Kliment Ohridski". [In Bulgarian].
Rhoades, R., & Bell, D. R. (2013). *Medical physiology: Principles for clinical medicine* (4th Ed.). Wolters Kluwer.
Sembulingam, K., & Sembulingam, P. (2012). *Essentials of medical physiology* (6th Ed.). Jaypee Brothers.
Sherwood, L., & Ward, C. (2019). *Human physiology: From cells to systems* (4th Ed.). Nelson.
Silbernagl, S., & Despopoulos, A. (2015). *Color atlas of physiology* (7th Ed.). Thieme.
Silverthorn, D. U. (2019). *Human physiology: An integrated approach* (8th Ed.). Pearson Education.
Sircar, S. (2014). *Principles of medical physiology* (2nd Ed.). Thieme.
Slominski, T., Grindberg, S., & Momsen, J. (2019). Physiology is hard: A replication study of students' perceived learning difficulties. *Advances in Physiology Education*, *43*(2), 121 – 127. https://doi.org/10.1152/advan.00040.2018.
Stanfield, C. L. (2017). *Principles of human physiology* (6th Ed.). Pearson.
Vitanova, L., & Garchev, R. (2020). *Fiziologiya na choveka* (3rd Ed.). Arso. [In Bulgarian]
Widmaier, E. P., Raff, H., & Strang, K. T. (2019). *Vander's human physiology: The mechanisms of body function* (5th Ed.). McGraw-Hill.
Yankov, E. (2013). *Fiziologiya. Uchebnik za studenti po meditsina. Tom 3* (3rd Ed.). Simel. [In Bulgarian]

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