Pharmacy Education (2020) 20(1) 324 - 335
https://doi.org/10.46542/pe.2020.201.324335

RESEARCH ARTICLE

What do pharmacy students need to know about biochemistry?

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Keywords
Assessment
Biochemistry
Course Design

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Abstract

Objective: The goal of this study was to determine what students need to know about biochemistry in order to practice pharmacy. **Methods**: With reference to a list of learning objectives, educators interviewed students during their advanced clinical rotations, asking if they had used each item in practice. Each item was then rated according to the number and strength of affirmative responses. The ratings were used to identify the elements of biochemistry most strongly recognised as relevant to clinical practice. **Results:** All of the learning objectives received affirmative responses, indicating that each was recalled or used by some respondent(s). The most highly rated objectives indicate aspects of biochemistry most closely related to clinical practice. **Conclusion:** The results provide guidance to educators for designing biochemistry courses, highlighting recognisable connections between biochemistry and clinical practice, and areas where relevance may need to be made clearer or re-evaluated.

Introduction

In recent years, pharmacy practice has changed to accommodate an expanding healthcare system and clinical expectations of those pharmacists. As such, many colleges and schools of pharmacy have re-envisioned their curricula to prepare students for the growing role of a pharmacist in a healthcare team (Romanelli, 2018). Biochemistry has long been accepted as the foundation for pharmacology , therapeutics and other content in the pharmacy curriculum, and therefore, directly or indirectly, for the actual practice of pharmacy (Lewis, 1947; Bauer, 1947; Woster, 2003; Broedel-Zaugg *et al*., 2008; Harrold & McFalls, 2010; Rose, 2011; Van Winkle *et al*., 2013; Goyal *et al*., 2014; Osheroff *et al*., 2015; Dirks-Naylor *et al*., 2015; Georgiev *et al*., 2016; Sánchez-Pozo, 2017; Gryka *et al*. 2017; Niederhoffer *et al*., 2017; Okubo *et al*., 2017). As such, biochemistry is typically taught early in the pharmacy curriculum, or it is a prerequisite for entry into some professional pharmacy programmes. Because of its foundational role, educators need to structure biochemistry course(s) so that they cover all of the competencies required of pharmacists, as thoroughly and concisely as possible. Further, the Accreditation Council for Pharmacy Education (ACPE), in the Standards 2016, underscore that pharmacists must 'employ evidence-based practice' and be able to 'apply foundational sciences to the provision of patient-centred care' (ACPE, 2016).

While pharmacy educators understand that biochemistry is an important area of the foundational sciences for pharmacy students, an agreement on necessary competencies related to practice is rarely discussed in the literature. A 2007-2008 study, for example, reported that two-thirds of a sample of administrators agreed that a

course in biochemistry should be required for admission to the professional pharmacy curriculum. The report indicated that a relatively small number of schools actually do require biochemistry for admission, but many schools include biochemistry in their curricula rather than having it as a prerequisite for admission (Broedel-Zaugg *et al*., 2008). A white paper prepared by the Biological Sciences Section of the American Association of Colleges of Pharmacy (AACP) included a section on the 'Biochemistry Core Knowledge and Skills' (competencies) that pharmacy school graduates need to possess (Personal Communication, Dr. Arbi Nazarian, Chair, Committee of Sections, AACP, 2014). Further, at the 2015 Conference of the Association of Biochemistry Course Directors (ABCD; since renamed the Association of Biochemistry Educators [ABE]), a panel of pharmacy educators presented and discussed a proposed list of biochemistry learning objectives for pharmacy education (Osheroff *et al*., 2015), aligned with the AACP Biological Sciences Section 'Biochemistry Core Knowledge and Skills' competencies. In this report, the authors will refer to this as the AACP/ABE list. The list included 131 learning objectives. Most recently, Das and colleagues speculated that the growing healthcare enterprise will lean heavily on pharmacists for medication management services, requiring both basic and clinical science knowledge, and sought to improve the relationship of pharmaceutical sciences to the clinical arena by providing students with case-based practice activities that focus on the tenets of medicinal chemistry (Das *et al.*, 2018).

Biochemistry educators have the knowledge, skills and experience necessary to develop courses in their area of expertise. However, feedback from practitioners, including student pharmacists engaged in clinical training, may be helpful in the design of courses to allow for relevance without unnecessarily expanding content. Advanced pharmacy students are able to, for example, reflect on which elements of biochemistry they utilise in their clinical practice. The authors reasoned this as one way of verifying the relevance of biochemistry for the practice of pharmacy. Such reflections can also help educators fine-tune their courses, highlighting areas on which they should focus, and providing first-hand feedback which may be used to explain the relevance of biochemistry in providing evidence-based, patient-centred care to their students.

The goal of the present study was to gather feedback from advanced pharmacy students about what biochemistry knowledge and understanding they are using in their clinical practice. This feedback will enable educators to better understand what concepts of biochemistry pharmacy students use and need to know in order to function as high-level pharmacy practitioners and will allow for re-tooling of the learning objectives associated with the courses that present the fundamental aspects of biochemistry.

Methods

Since 2015, a group of biochemistry educators in seven schools of pharmacy have conducted interviews with advanced students (students doing their Advanced Professional Practice Experience [APPE] rotations) to determine what information, from the AACP/ABE list of learning objectives, these students have used in their clinical practice education. The original study group included educators from 17 institutions and all were invited to conduct interviews, but only seven actually did so. The institutions where the interviews were conducted were: MCPHS University, School of Pharmacy, Worcester, MA; St. Louis College of Pharmacy (STLCOP), St. Louis, MO; University of Kentucky (UK), College of Pharmacy, Lexington, KY; Chicago State University (CSU), College of Pharmacy, Chicago, IL; Samford University (SU), McWhorter School of Pharmacy, Birmingham, AL; Drake University (DU) College of Pharmacy and Health Sciences, Des Moines, IA; Presbyterian College School of Pharmacy (PCSP), Clinton, South Carolina. Approval for conducting this study was sought and obtained from the Institutional Review Boards of these institutions.

Over the course of two academic years (2015-2017), the educators interviewed 70 APPE students. A preliminary report on this project, based on the first 32 interviews (a pilot study), was presented at the 2017 Conference of the Association of Biochemistry Educators (Niederhoffer *et al*., 2017).

Students who agreed to participate in the study were interviewed individually, orally, and in-person. Each interviewee received, reviewed, and signed an Informed Consent document, indicating her/his willingness to participate in the study. This document explained the purpose of the study, that participation in the study was voluntary, how the interview would be conducted, and the confidential nature of the study. Each interviewee was assigned a participant ID number, and all remaining documents included that number, but no participant name. Participants completed a registration form, including demographic information, and information about their educational background.

For each interview, the interviewer went through the AACP/ABE list, asking the interviewee, with regard to each

learning objective, to cite a clinical situation during APPE rotations wherein she/he had used that piece of knowledge/information. The interview questions were pre-formulated so that each student was asked the same questions. Each interviewer recorded and took notes on the interviews, and entered notes summarising each participant's comments about each learning objective in a spreadsheet. After all of the interviews had been conducted, the interviewers' spreadsheets were submitted to the study co-directors, who merged all reported comments into a master spreadsheet.

In accord with best practices for conducting qualitative research (Patton, 1999; Merriam, 2009; Patton, 2015; O'Sullivan, 2017; O'Sullivan, 2018), the study co-directors analysed the collected data as follows.

Since interviewees were asked to cite a clinical situation during APPE rotations wherein she/he had used that piece of knowledge/information, the initial analysis involved categorising each response as either affirmative (if a clinical application was cited) or negative (for any other response). Upon further review of the responses, however, it became clear that a more nuanced analysis was called for. Based on a review of all of the recorded responses, a rating system was therefore devised, assigning a number of points to each response, as follows:

- 3 points if the interviewee cited a clinical application (e.g., a disease state, such as diabetes) or a specific rotation during which the topic was relevant
- 2 points if the interviewee/interviewer indicated clearly that the topic was important (using words such as 'Yes 'or 'Good', or elaborating on the topic to illustrate understanding) but did not explicitly indicate a clinical application
- 1 point if the interviewee/interviewer indicated some connection to the topic, using a word such as 'Weak' or 'Basic', but no clinical application
- 0 points if there was a negative response (No) or no response at all (blank), or if the comment had nothing to do with the specific learning objective

For each of the 131 items, one of the study co-directors rated each response. The numbers of 3, 2, 1, and 0 ratings for each item were then tabulated.

When categorising or rating qualitative responses, it is possible that a rater may be biased - for example, tending to rate responses relatively high in order to make the clinical relevance of items appear strong. In order to establish the credibility and validity of ratings, it is therefore important to test for rater bias by having two or more raters categorise responses.

Additionally, if the definitions of the categories of responses are not clear and unambiguous, it is possible that different observers will rate responses differently. In order to demonstrate the validity of the rating system it is important to demonstrate that independent raters will categorise responses similarly.

As a way of establishing the validity of ratings, by checking for bias and making sure that independent raters categorise responses similarly, Merriam (2009) and Patton (1999; 2015) suggest 'analyst triangulation', having two or more persons independently analyse data and compare their results. To do this for the present study, the study director initially rated all responses, and then two of the co-authors, without seeing the initial ratings, each rated all 70 reported responses to two-thirds of the items. With this system, every item was rated by the primary rater and one or two independent secondary raters. To assess inter-rater agreement, Cohen's kappa (Cohen, 1960) was calculated for each secondary-primary rater pair.

Results

Seventy APPE students from seven colleges of pharmacy in the United States of America (USA) (Table I), were interviewed for this study. Participants included 20 students from MCPHS University, 15 from CSU, 14 from DU, 11 from UK, 5 from PCSP, 4 from SU, and 1 from STLCOP. The majority of the participants (78.6%, n=55) attended four-year degree programmes at CSU, UK, PCSP and SU, or a three-year accelerated programme at MCPHS, while the remaining students were enrolled in the six-year degree programmes at DU and STLCOP. With the exception of one student enrolled in STLCOP, all students completed biochemistry in their first year of the pharmacy curriculum. Students attending MCPHS, CSU and UK completed a two-semester biochemistry course sequence, while students from PCSP, DU and SU completed a one semester course.

The majority of the participants were female (65.7%; n=46). Most student participants fell within the age ranges of 21-27 (n=51). The most diversity was observed in students from CSU, DU and MCPHS (Table I). A slight majority of the participants (n=37, 52.9%) obtained a B.A./B.S. prior to entering pharmacy school, while 31.4% participants reported completing some college (n=22). A little more than 50% of students (n=36) reported completing a separate biochemistry course prior to entering the Pharm.D. programme (Table I). An equal number of participants reported receiving an A or B (44.3%, n=31) while the remaining reported earning a C in their pharmacy biochemistry courses (Table I).

Table I: Demographic information of student participants

Variables	Total	Chicago State University	Drake University	MCPHS University	Presbyterian College School of Pharmacy	Samford University	St. Louis College of Pharmacy	University of Kentucky
	N=70 (%)	N=15 (%)	N=14 (%)	N=20 (%)	N=5 (%)	N=4 (%)	N=1 (%)	N=11 (%)
Gender								
Female	65.7	73.3	64.3	65	80	25	100	63.4
Male	32.3	26.7	35.7	35	20	75	0	36.4
Age in years								
21-24	31.4	6.6	78.6	20	20	50		36.4
25 - 27	41.4	26.7	14.3	45	80	25	100	63.6
28-34	22.9	60	7.1	30				
35 or older	4.3	6.6		5		25		
Race/Ethnicity								
White	57.1	20	78.6	30	100	100	100	90.9
African American	14.3	33.3	7.1	20				
Asian/Pacific Islander	27.1	40	14.3	50				0.9
Hispanic/Latino	1.4	6.6						
Highest Level of Education								
Some College	31.4	20	100			60		27.3
Associates Degree	5.7	6.6						0.9
BA/BS	52.9	66.7		90			100	51.6
MA/MS	4.3			10				
Pharm.D.	5.7	6.6				40		0.9
Completed Biochemistry Course Prior to Entering Pharmacy School								
Yes	51.4	53.3	28.6	65	25	50	100	65
No	48.6	46.7	71.4	35	75	50		35
Grade Received								
A	44.3	26.7	78.6	25	40	25	100	35
B	44.3	66.7	21.4	50	20	75		65
C	11.4	6.7		25	40			

Table II: Number of rotations required for each programme

Institution	Number of Rotations
MCPHS University	6
Chicago State University	7
University of Kentucky	7
Samford University	8
St. Louis College of Pharmacy	8
Drake University	9
Presbyterian College School of Pharmacy	9

The APPE rotation requirement for graduation varied from six to nine modules at the universities participating in the study (Table II). The length of the rotations varied from four to six weeks. On average, participants completed six (SD±1.4) rotations prior to participating in the study. The majority of the participants had completed the core rotations in Ambulatory care (n=58), Community Pharmacy (n=59), Hospital/Institutional (n=62) and Medicine (n=52) (Table III). Among the electives, Critical Care and Infectious Disease were reported most frequently by student participants (Table III).

Table III: Completed rotations reported by student participants

Rotation	Total N=70 (%)
Required	
Ambulatory Care	82.9
Community Pharmacy	84.3
Hospital/Institutional	88.6
Medicine	74.3
Elective	
Critical Care	41.4
Infectious Disease	22.9
Oncology	14.3
Pediatrics	10.0
Psychology	12.9

Table IV: Examples of reported comments to illustrate ratings

Rating	Illustrative comments
3 - if the interviewee cited a clinical application (e.g., a disease state, such as diabetes) or a specific rotation during which the topic was relevant.	pH/pKa (LO 1): "*Yes, related to excretion. Charge as function of pH. Transport. Solubility. Esp. during Institutional rotation*."
	Hemoglobin (LO 26): "*Very important, esp. for ICU rotation: patient blood O2 level, Hct, etc.*"
	Carbohydrate metabolism (LO 68): "*Yes, for diabetic patients - especially response to insulin and glucagon (also with regard to beta blockers)*"
	Vitamins (LO 121): "*Patients taking Orlistatat may have to supplelement A, D, E, K. Talked about Scurvy. Anemia patients may have B vitamin deficiencies*."
2 - if the interviewee/interviewer indicated clearly that the topic was important (using words such as Yes or Good, or elaborating on the topic to illustrate understanding) but did not explicitly indicate a clinical application.	pH/pKa (LO 1): "*Can't give a clinical experience that can think of in head that have had to use towards APPE rotation. Have used in other classes down the road. pKa or pH of a drug - for like calculations (introduced in biochem and reinforced in another class*."
	Acid-Base (LO 2): "*Henderson-Hasselbalch used in pK class, not in rotation*."
	Stereochemistry of monosaccharides (LO 6): "*Some drugs have S & R config.: some active, some not.*"
	Glycosidic bond between monisaccharides (8/10-20): "*Stereochemistry - in med chem, not in practice*"
1 - if the interviewee/interviewer indicated some connection to the topic, using a word such as Weak or Basic, but no clinical application.	Weak interactions (LO 4): "*Not specifically, but may be on a broad level the concept of hydrophobicity etc.*"
	Regulation of carbohydrate metabolism (66/116): "*Biochem/Med Chem lecture*"
	Urea cycle (80/143-45): "*get waste out of the body, protect pH*"
	ATP:ADP ratio and regulation (109/234-45): "*Feedback mechanism*"

The compiled ratings of the learning objectives can be found in Appendix A. Table IV shows a sample of reported comments, to illustrate ratings assigned to those comments.

Table V: Number of items receiving specified number of ratings of 3

No. of ratings of 3	No. of items
0-9	58
10-19	35
20-29	21
30-39	13
40-49	2
50+	2

How to read the table: *Seventy [70] interviewees commented on each of the 131 items. The study director rated each of the comments on each item on a scale of 0-3. Example: 35 of the 131 items received 10-19 ratings of 3.*

Highlights of the ratings are as follows: the number of respondents indicating that they had used a given piece of information in a clinical situation (a rating of 3) ranged from 0 to 52. The descriptions of the ratings can be found in the Methods section above, and that a rating of 3 indicated that the interviewee had cited a clinical application e.g., a disease state, such as diabetes or a specific rotation during which the topic was relevant. Table V shows the number of items receiving ratings of 3.

Table VI: Most highly rated learning objectives

Learning Objective(s)	L.O. Number(s) (Appendix A)
Vitamins, cofactors, and their role in metabolism	120, 121
Hemoglobin and its role in transport	26
pH, pK_a, and the dissociation constant, K_d	1
Carbohydrate metabolism, its regulation, and the connection to disease states such as diabetes	60, 65, 68, 74, 118
Enzyme inhibition, and the connection to drugs that are inhibitors	40, 41
Lipids and their metabolism, including cholesterol; the role of HMG-CoA reductase, and the action of statins; lipoproteins; ketone bodies	16, 18, 93, 94, 95, 98
DNA and DNA processes, and antibacterial and anticancer drugs that affect these processes	57, 58
Pharmacogenomics	131

Check for inter-rater agreement: as detailed in the Methods section above, after one of the study co-directors (the 'primary rater') had rated each response to the 131 items, each of two of the co-authors (the 'secondary raters'), without seeing those ratings, did the same for approximately two-thirds of the items, so that every item was rated by two independent observers. Their ratings were then compared to the primary ratings, and

Cohen's kappa (κ) was calculated for each primary-secondary pair (Cohen, 1960). The values of κ for the two pairs were 0.87 and 0.81. There is no general agreement as to what magnitude of κ reflects adequate agreement, but Landis & Koch (1977) suggested guidelines that authors often reference: κ values of 0.41-0.60 represent 'moderate agreement', values of 0.61-0.80 represent 'substantial agreement', and values of 0.81-1.00 represent 'almost perfect agreement' (Woster, 2003).

Among the learning objectives that were most highly rated (Appendix A), with the highest number of 3 ratings were those related to the following topics:

- vitamins, cofactors, and their role in metabolism (L.O. #120, 121)
- haemoglobin and its role in transport (L.O. #26)
- pH, pKa, and the dissociation constant, Kd (L.O. #1)
- carbohydrate metabolism, its regulation, and the connection to disease states such as diabetes (L.O. #60, 65, 68, 74, 118)
- enzyme inhibition, and the connection to drugs that are inhibitors (L.O. #40, 41)
- lipids and their metabolism, including cholesterol; the role of HMG-CoA reductase, and the action of statins; lipoproteins; ketone bodies (L.O. #16, 18, 93, 94, 95, 98)
- DNA and DNA processes, and antibacterial and anticancer drugs that affect these processes (L.O. #57, 58)
- pharmacogenomics (L.O. #131)

Interviewees indicated that they had used information related to the above topics during their APPE rotations (rating of 3) or that they understood the importance of the topic (rating of 2).

Discussions and Conclusion

The results of this study indicate that all of the aspects of biochemistry covered by the 131 learning objectives were recalled by students, and many were recognised as relevant during the students' APPE rotations.

One might expect that in a perfectly aligned curriculum, everything taught in didactic course would be applied in experiential education. This might lead to an expectation that students interviewed for this study would report using almost every one of the 131 biochemistry learning objectives during their APPE rotations. The authors submit, however, that there are many possible reasons to explain why not every student reported using every piece of information in a clinical setting:

In order for a student to indicate that she/he had used, in a clinical setting, a specific piece of information from a biochemistry course two or more years earlier, the student would have to have almost perfect memory - remembering all patient cases from all rotations, and remembering and understanding everything that was taught in the biochemistry course. If a student did not recall all of this, that student would not remember all of the pieces of biochemistry information that she/he drew on in clinical situations. Because of this imperfect recall, it is likely that students drew on biochemistry information more often than they remembered. For this reason, the authors submit that the relative number of acknowledged connections probably indicates the relative importance of the items (learning objectives) to clinical practice, but that the number of actual connections is probably much greater than the number of remembered connection.

Students were interviewed at different times during their final year in pharmacy school, during which they would complete a total of six-nine rotations. Students who participated in the study had not yet completed all of their rotations at the time of their interviews, so they had not yet had clinical experiences related to some of the biochemistry they had learned. For example, 17% had not yet completed the required Ambulatory Care rotation, 16% had not yet completed the required Community Pharmacy rotation, 11% had not yet completed the required Hospital/Institutional rotation, and 26% had not yet completed the required Medicine rotation (Table III).

Some students may not consciously recognise that they are applying biochemistry in their APPE rotations. This could be because a significant amount of time had passed since they had taken a biochemistry course, because they had forgotten the biochemical underpinnings of other subjects they had studied (e.g., pharmacology), or because of a host of other reasons. It could be that biochemistry, or a biochemical way of thinking, could be embedded in their thinking at a subconscious level.

Some of the learning objectives may be so granular that interviewees replied that they never applied the objectives during their clinical experiences, even though there was important general information in the objectives. For example, students may never have had to 'apply the Henderson-Hasselbalch equation to solve pH problems', but they may have had to understand how pH can affect the charge on molecules, such as various drugs.

It was clear from comments made by interviewees that different preceptors emphasised different topics, and

different sites offered different learning opportunities. For example, one preceptor might highlight amino acids as part of Total Parenteral Nutrition, while another might not. This certainly accounts for some of the variability in responses about clinical application of biochemistry.

Beyond these possible reasons for low ratings, it is nevertheless important to include some biochemistry in a course even if not every student absolutely needs to know it in order to successfully complete every APPE rotation. Whether or not students realise it, they need to know some parts of biochemistry as prerequisites for courses they will take subsequently (e.g., medicinal chemistry), and they may need to know some things that they will not apply in their APPE rotations but which they may apply over the course of their professional practice, such as the growing field of pharmacogenomics (Weitzel *et al*., 2016).

The reliability of the ratings in this study is important. This was assessed by comparing the ratings, carried out independently, of the primary study director and two co-directors. The fact that independent assessors rated the responses very similarly (kappas of 0.87 and 0.81) suggests that the rating rubrics were clear, and that the ratings were not substantially affected by rater bias.

While the low ratings for some learning objectives may be concerning, lack of high ratings for every item is understandable, especially in view of the limitations discussed above. Instead of focusing on absolute numbers, the authors submit that what is important to focus on is the relative ratings of the items. Specifically, the results of this study provide guidance to educators as they design biochemistry courses in pharmacy curricula. Relatively highly-rated learning objectives appear to have high clinical relevance, and biochemistry educators would do well to highlight this in their teaching. When teaching material related to objectives with lower ratings, educators may need to provide extra information to make their practice relevance clear. In some cases, though, it may be that these objectives are less important for pharmacy students, or that they are more specific than they need to be. The authors submit that a revised list of learning objectives should include less-specific (and therefore less limiting) items, highlighting broader but critically important information. The criteria for including items should be that they are essential for progressing to subsequent courses in the curriculum, and essential for pharmacists to competently practice their profession, upon graduation and licensure, and over their entire career.

The focus of the present study was on pharmacy education in the USA. The referenced competencies and learning objectives were from sub-groups of, respectively, the AACP and the ABE, both of which are primarily USA-based organisations. This means that the study is most relevant for USA-based educators, but the competencies and learning objectives are probably similar for educators world-wide. Having said that, it would certainly be worthwhile to carry out similar studies in the future about teaching biochemistry in pharmacy programmes in countries other than the USA.

The approach of the present study could also be extended to the teaching of biochemistry to students in other healthcare professions (e.g., medicine, physician assistant, dentistry). The ABE includes educators from schools of medicine and dentistry and may be interested in such studies. Comparative analyses of such results would be valuable for further improving basic sciences curricula in pharmacy as well as other healthcare professions. Finally, it would be interesting to explore the effectiveness of various methods for teaching biochemistry (and other subjects), some of which have been necessitated by the COVID-19 pandemic.

This study may also inspire faculty in undergraduate Allied Health Sciences' courses to conduct similar studies for their students. For example, they may wish to explore what organic or analytical chemistry students need to know in order to succeed in other courses in a pharmaceutical sciences curriculum.

As noted in the Introduction, educators generally agree about the importance of biochemistry in the education of pharmacists, and biochemistry competencies have been proposed (Nazarian *et al*., 2014). What the present study adds to the literature is practice-based evidence of the relevance and importance of specific elements of biochemistry that underlie the practice of pharmacy. In addition to providing course-design guidance to educators, this also highlights the advantage of including biochemistry in the pharmacy curriculum, rather than just as a prerequisite for admission, because pharmacy educators can make explicit connections between biochemistry and the practice of pharmacy.

Acknowledgements

The authors thank the following colleagues who conducted interviews at their institutions: Paul Juang (Pharm.D.), St. Louis College of Pharmacy; Danielle Cruthirds (Ph.D.), Samford University, McWhorter School of Pharmacy; and David Eagerton (Ph.D.), Presbyterian College School of Pharmacy (now at Campbell University, College of Pharmacy and Health Sciences).

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Appendix A

	Competencies (Biological Sciences Section of AACP)	LO No.	Learning Objectives (Association of Biochemistry Course Directors)	No. of ratings			
				0	1	2	3
	Basics	1	Define and explain pH, pK, and the dissociation constant K_d.	8	2	28	32
		2	Apply the Henderson-Hasselbalch equation to solve pH problems	39	4	20	7
		3	Define and explain Gibbs free energy (ΔG), standard free energy (ΔG˚˚), and the equilibrium constant (K_{eq}) as it applies to biochemical reactions.	62	5	2	1
		4	Define and explain the roles of Van der Waals forces, charge-charge interactions, hydrogen bonds, and hydrophobic interactions in protein and macromolecular architecture and indicate how these forces differ from covalent bonds.	28	10	16	16
1	**Structure of the essential biological building blocks**: Student Pharmacist should be able to describe the functional groups and elements that characterize amino acids, carbohydrate, nucleotides and lipids and evaluate their physical and chemical properties.	5	Describe the general structure of monosaccharides, and classification by size and type of carbonyl functional group.	32	1	15	22
		6	Describe the stereochemistry of monosaccharides and what is meant by stereoisomer, enantiomer, diastereomer and epimer.	27	6	26	11
		7	Describe the cyclic structure of monosaccharides and the definition of α- and β-anomers.	58	4	7	1
		8	Describe a glycosidic bond, and how a glycosidic bond between sugar molecules is identified.	46	2	20	2
		9	Describe the structural differences between starch and glycogen.	45	3	8	14
		10	Demonstrate that you know the structures of the 20 amino acids that commonly occur in proteins and classify them according to chirality, polarity, and charge.	44	9	6	11
		11	Know the 3 letter codes identifying the 20 standard amino acids and selenocysteine.	43	2	3	22
		12	Determine the charge on an amino acid at a given pH.	56	3	3	8
		13	Explain what is meant by the isoelectric point (pI) of an amino acid.	59	1	8	2
		14	Name the major purine and pyrimidine bases and identify amino acid and one-carbon metabolites that contribute to the synthesis of these ring structures.	40	1	17	12
		16	Name common fatty acids and classify as saturated, monounsaturated, or polyunsaturated.	23	3	11	33
		17	Describe the composition and structure of triglycerides, phosphatidyl lipids and sphingolipids.	37	3	14	16
		18	Describe the structures of cholesterol, steroids, and cholesterol ester.	27	1	13	29
1a.	**Cell Biology**	19	Define micelles and liposomes and describe how they are formed spontaneously from detergent, bile acids, and phospholipids.	28	7	11	24
		20	Describe the role of collagen and elastin in connective tissue	47	0	10	13
2	**Structure and function of proteins and enzymes**: Student Pharmacist should be able to describe the different levels of protein structural organization, describe the forces that stabilize proteins and their interaction other biomolecules. Describe the properties of enzymes, the catalytic strategies they use, explain the parameters that are used to characterize enzyme activity and evaluate the different types of enzyme inhibitors.	21	Describe the bonds and forces (peptide, disulfide, and hydrogen bonds; hydrophobic, dipole-dipole, van der Waals and electrostatic interactions) that contribute to the conformation of proteins and the interaction of proteins with other biomolecules.	38	6	9	17
		22	Define and discuss the following terms: peptide bond, peptide backbone, N-terminus, C-terminus, disulfide bridges, α-helices, β-sheets, β -strands, β -turns.	41	9	12	8
		23	Discriminate between primary, secondary, tertiary, and quaternary protein structure.	41	7	8	14
		24	Determine the charge on a small peptide at a given pH	56	6	3	5
		25	Define and explain the role of membrane proteins	34	6	10	20
		26	Explain the role of hemoglobin in the delivery of oxygen, removal of waste and buffering.	7	6	7	50
		27	Describe the structural difference between hemoglobin, myoglobin and methemoglobin (oxidized hemoglobin) and compare O_2 binding properties of hemoglobin, methemoglobin and myoglobin.	42	7	4	17
		28	Describe the 6 major enzyme classifications and the basic type of reaction catalyzed, including: oxidoreductases, transferases, hydrolases, lyases, isomerases, and ligases.	34	12	5	19
		29	Define and describe the roles of the following enzyme-related terms: zymogen/ proenzyme, coenzyme, co-factors, prosthetic group, apoenzyme, holoenzyme, and isozymes.	42	3	1	24
		30	Explain how an enzyme functions as a catalyst in lowering the activation energy of reactions.	43	0	15	12
		31	Propose a thermodynamic explanation of why enzymes cannot alter the equilibrium of reactions.	58	3	8	1
		32	Define the term transition state and propose a role for the transition state in lowering activation energy.	55	10	4	1
		33	Explain how transition state inhibitors work as drugs.	53	3	6	8
		34	Explain the induced fit (conformational change) model of enzyme catalysis.	42	0	16	12
		35	Name an example and describe basic catalytic mechanisms, including: serine proteases, covalent and acid-base catalysis.	51	9	6	4
		36	Define initial velocity (V_0) and explain the effect of substrate concentration on enzyme velocity for a single subunit enzyme.	59	4	3	4
		37	Explain Michaelis-Menten kinetics and be able to apply the Michaelis-Menten equation to calculate velocity, maximum velocity (V_{max}) and the Michaelis constant (K_m).	44	8	8	10
		38	Describe the significance of an enzyme's Km value in metabolic systems.	43	3	14	10
		39	Draw a Lineweaver-Burk plot, defining V_{max} and K_m and use the plot to evaluate types of inhibition, including: competitive, non-competitive, and mixed inhibition in drugs.	49	5	6	10
		40	Compare and contrast the different types of inhibitors, with examples including: transition state inhibitors, suicide inhibitors, irreversible inhibitors, competitive and noncompetitive inhibitors.	17	0	15	38
		41	Evaluate the difference between a competitive versus non-competitive drug inhibitor (e.g. using fomepizole and ethanol treatments for methanol poisoning.)	23	0	15	32
		42	Define and explain allosterism and the important physiological role of allosteric enzyme inhibition or activation.	49	3	13	5
		43	Define and compare and contrast feed-back versus feed-forward regulation.	32	1	15	22

		44	Explain the role of post-translational modifications in regulating enzyme activity, including: proteolysis, and reversible phosphorylation.	48	3	12	7
		45	Propose why some enzyme reactions are considered irreversible in the cell.	50	2	11	7
3	**Structure of DNA, DNA damage and repair, replication, transcription and translation of genetic information**: Student Pharmacist should be able to describe the structure of DNA, how it is damaged and the repair mechanisms. Describe how genetic information is organized and expressed within cells. Describe the processes of replication, transcription and translation, comparing them in eukaryotes and prokaryotes. Identify relevant diseases associated with DNA processed and therapeutic targets.	46	Summarize the central dogma of molecular biology, and cite the exceptions, notably in viruses.	30	0	16	24
		47	Describe the chemical composition of DNA, its structure, and its relationship to the processes of replication, transcription, recombination and repair.	31	0	15	24
		48	Summarize the mechanism of DNA replication.	41	7	7	15
		49	Compare and contrast polymerase proofreading, direct repair, base excision repair, nucleotide excision repair, mismatch repair, and recombination.	50	6	8	6
		50	Name the different types of mutations that occur in DNA.	42	0	12	16
		51	Describe the chemical composition of RNA.	48	0	15	7
		52	Summarize the initiation, elongation, and termination of transcription, comparing and contrasting these processes in eukaryotic and prokaryotic cells.	50	2	11	7
		53	Describe the universal features of the genetic code and its biological relevance.	47	1	14	8
		54	Summarize the three steps of protein synthesis (translation): initiation, elongation, and termination. Compare and contrast these processes and their regulation in eukaryotic and prokaryotic cells.	39	3	10	18
		55	Describe the mechanisms of gene regulation, both negative and positive, as exemplified by prokaryotic systems.	52	0	14	4
		56	Describe eukaryotic gene structure and the role of chromatin in making DNA accessible for biological processes	54	7	7	2
		57	Describe how DNA and DNA processes can be used as therapeutic targets (e.g. anticancer and antibacterial drugs).	24	2	10	34
		58	Summarize why mutations in DNA repair systems can lead to disease, including certain types of cancer.	30	1	12	27
4	**Metabolic pathways for biosynthesis and degradation of carbohydrate, amino acids, nucleotides and lipids:** Student Pharmacist should be able to describe the different components of each metabolic pathway, identify the metabolites that integrate different metabolic pathways and explain how metabolic pathways are regulated. Students should also be able to interpret metabolic changes in terms of carbohydrate lipid, amino acid and lipid metabolism.	59	Evaluate and predict the effects of partial or complete enzyme deficiency on a metabolic pathway.	37	5	7	21
		60	Describe the overall purpose of glycolysis, its reactants and products, its cellular localization and tissue distribution.	26	9	2	33
		61	Describe the roles of hexokinase/glycokinase, phosphofructokinase-1 (PFK-1) and pyruvate kinase in glycolysis, and the mechanisms (allosteric, covalent modification) by which their activity is regulated.	56	7	2	5
		62	Describe the purpose of the reaction catalyzed by lactate dehydrogenase, its reactants and products, cellular and tissue localization and how it is regulated.	51	4	5	10
		63	Explain the concept of substrate-level phosphorylation and why it is important.	58	4	6	2
		64	Describe the role and fate of the cytosolic NADH produced in glycolysis	56	6	6	2
		65	Describe the overall purpose of gluconeogenesis, its reactants and products, its cellular location and its tissue distribution.	22	5	9	34
		66	Describe the roles of pyruvate carboxylase, PEP carboxykinase, fructose-1,6-bisphosphatase and glucose-6-phosphatase, and the mechanisms by which their activity is regulated.	57	10	1	2
		67	Evaluate the relative importance of different precursors for gluconeogenesis in feeding, fasting and exercise.	34	5	5	26
		68	Explain how the activities of glycolysis and gluconeogenesis are regulated in relationship to fatty acid and protein metabolism, and in response to glucagon and insulin	15	3	8	44
		69	Describe the overall purpose of the pentose phosphate pathway, its reactants and products, its cellular location and its tissue distribution	57	11	2	0
		70	Describe the overall purpose of glycogenesis and glycogenolysis, their reactants and products, their cellular localization and tissue distribution.	41	8	6	15
		71	Describe the roles of glycogen synthase and branching enzyme in glycogenesis and predict the biochemical consequences in deficiencies of these enzymes.	60	3	3	4
		72	Describe the roles of glycogen phosphorylase, debranching enzyme, and glucose-6-phosphatase in glycogen breakdown and predict the biochemical consequences in deficiencies in these enzymes.	59	4	3	4
		73	Compare and contrast the purpose and regulation of glycogenolysis in hepatocytes versus skeletal muscle.	57	4	1	8
		74	Explain how glycogen synthesis and glycogenolysis are regulated by insulin, glucagon and catecholamines.	27	3	13	27
		75	Explain the contribution of glycogenolysis and glycogenesis to blood glucose regulation during the fed state, the fasting state and exercise	34	1	11	24
		76	Describe the overall purpose of the pyruvate dehydrogenase complex, its reactants and products, its cellular localization and tissue distribution	59	6	3	2
		77	Describe the regulation of the PDH complex and the cellular conditions when the enzyme will be active or inactive	68	1	1	0
		78	Describe the dynamics of the free amino acid pool, including (A) inputs from diet, body protein breakdown, and *de novo* synthesis, and (B) outputs to protein synthesis, urea production, synthesis of specialized products and other metabolic processes	47	7	3	13
		79	Describe the activation of pancreatic zymogens and the roles of the active enzymes in protein digestion	54	1	3	12
		80	Explain the rationale of the urea cycle in ammonia excretion	42	10	3	15
		81	Define essential, conditionally essential, and nonessential amino acids, and list them accordingly	47	6	11	6
		82	Explain the role of transamination reactions in amino acid synthesis and identify the vitamin essential for this reaction (tie in to urea cycle)	62	3	1	4
		83	Define ketogenic and glucogenic amino acids, and list them as exclusively ketogenic, glucogenic, or both	64	2	1	3
		84	Describe the biosynthesis of the purine and pyrimidine nucleotides with emphasis on the key regulated steps.	54	4	4	8
		85	Explain the salvage pathways for uracil and thymine and their relevance to pharmacotherapy (such as for the treatment of cancer or herpes infections).	57	5	2	6
		86	Connect the pentose phosphate pathway to 5'phosphoribosyl-1-pyrophosphate (PRPP) synthesis and explain the central role of this metabolite in nucleotide metabolism.	66	3	1	0

		87	Summarize folate metabolism and explain its connection to nucleotide metabolism (such as the synthesis of thymidine and IMP)	39	5	1	25
		88	Describe the pathway of fatty acid synthesis and in particular the role of acetyl-CoA carboxylase and fatty acid synthase.	53	8	2	7
		89	Explain the concepts of elongation and desaturation of the fatty acid chain.	65	3	2	0
		90	Describe the synthesis and catabolism of triglycerides	48	2	3	17
		91	Describe the mechanism for activation and transport of fatty acids into mitochondria for catabolism.	64	2	2	2
		92	Outline the sequence of reactions involved in oxidation of fatty acids in mitochondria	64	2	3	1
		93	Explain the mechanism for the formation of ketone bodies and identify the physiological and pathological roles of those molecules	31	3	5	31
		94	Describe the stages of cholesterol synthesis and in particular the role of HMG-CoA reductase	22	1	2	45
		95	Explain the regulation of cholesterol clearance from blood through the LDL receptor.	27	0	8	35
		96	Summarize the role of cholesterol in the synthesis of bile acids, steroids and vitamin D	42	1	6	21
		97	Compare and contrast the life cycle of the various lipoprotein particles with respect to their composition, metabolism and transport	57	2	3	8
		98	Distinguish the effects of feeding, fasting, exercise and hormonal regulation on body lipids. Differentiate the contribution of diet and endogenous synthesis to lipid levels.	32	1	5	32
		99	Detail the mechanism by which energy charge regulates lipid metabolism.	63	0	1	6
		100	Describe the endocrine function of adipose tissue	59	0	4	7
		101	Describe the overall purpose of the citric acid cycle (CAC), its cellular location and tissue distribution.	64	0	1	5
		102	Describe the reactants and products of the CAC, as related to the fates of the breakdown products of carbohydrates, fatty acids and amino acids.	60	1	3	6
		103	Describe the roles of CAC intermediates as sources of reactants for biosynthetic pathways.	68	1	0	1
		104	Explain the effect of the following parameters on the activity of the CAC and the mechanisms by which the effect occurs: mitochondrial NADH/NAD ratio, ATP/ADP ratio, succinyl-CoA concentration.	67	0	1	2
		105	Describe the central role of the CAC in connecting glycolysis, gluconeogenesis, oxidative phosphorylation, fatty acid metabolism and amino acid metabolism	61	2	3	4
		106	Describe the purpose of the electron transport chain (particularly complexes I, III and IV) and ATP synthase, their substrates and products, cellular location and tissue distribution.	42	0	17	11
		107	Explain how electron transport and ATP synthase are functionally coupled.	53	6	7	4
		108	Explain how the process of oxidative phosphorylation is influenced by the availability of oxygen and NADH.	53	6	7	4
		109	Explain how the cellular ATP:ADP ratio regulates the rate of ATP production by oxidative phosphorylation.	56	12	1	1
		110	Discuss how succinate dehydrogenase, mitochondrial glycerol-3-phopshate dehydrogenase and acyl-CoA dehydrogenases transfer electrons to ubiquinone from succinate, cytosolic NADH and acyl-CoA, respectively.	63	3	2	2
		111	Describe the effects of electron transport chain inhibitors, ATP synthase inhibitors and uncouplers on oxidative phosphorylation and predict the effects of these agents on glycolysis, the citric acid cycle and lactate production	56	4	6	4
		112	Describe the types of Reactive Oxygen Species (ROS) and how they are generated	54	3	6	7
		113	Identify the metabolic products of ethanol metabolism, including acetyl-CoA	46	4	6	14
		114	Describe the properties of receptor-ligand interactions	37	1	14	18
		115	Describe the role of signal transduction pathways in controlling normal cellular, systemic and organismal functions.	43	2	11	14
		116	Describe how alterations in signal transduction pathways can lead to human disease	41	0	12	17
		117	Compare and contrast how each of the following affects glucagon secretion: glucose, amino acids, ketone bodies, epinephrine.	32	3	7	28
		118	Describe the effect of glucagon on metabolic processes in the liver and how this hormone functions to regulate blood glucose homeostasis	28	2	7	33
5	**Signaling mechanisms hormones and diabetes**: Student Pharmacist should be able to explain how hormones lead to changes in intracellular gene expression and metabolism. Describe the key second messengers and some specific signaling mechanism (e.g. G Protein coupled receptors).	119	Signaling	35	0	14	21
6	**Function of vitamins and minerals in metabolism and its implication in diet**: Student Pharmacist should be able to describe the essential vitamin and minerals needed for human health, describe the amounts needed in the diet and be able to identify different dietary sources noting their relative richness. Describe the function of vitamins and minerals in enzymatic reaction.	120	Know the vitamins that are precursors of the following cofactors: NAD and NADP (niacin), FMN and FAD (riboflavin), TPP (thiamin), THF (folate), Coenzyme A (pantothenate), PLP (B_6), B_{12}, Biotin.	18	12	1	39
		121	Know the main metabolic roles of, and the main consequences of deficiencies or excessive intake of, the B vitamins, vitamin C, and vitamins A, D, E and K	5	9	4	52
		122	Define essential and list examples of essential, conditionally and non-essential nutrients	39	1	4	26

7	**Structure and function of biological membranes**: Student Pharmacist should describe the structural components of biological membranes and their physical properties. Describe how proteins are associated with biological membranes and relate how the type of protein association relates to its biological function. Describe the role of biological membranes in drug absorption, distribution and action.	123	List and describe the physiological roles of membranes including: compartmentation, electrochemical/membrane potential, transport, anchoring.	38	5	9	18
		124	List and describe the roles of each of the major components of membranes and integrate each into a working model of a generic membrane, including: phospholipids, sphingolipids, cholesterol, and protein [for example lipid rafts and caveola].	32	8	7	23
		125	Explain the role of membrane fluidity and describe how it can be altered by biological processes.	41	8	7	14
		126	List the various specific types of major membrane lipids and describe the role of membrane asymmetry.	59	3	6	2
7a.	**(Transport)**	127	Name two examples each of passive diffusion, active transport, and facilitated transport via a channel or carrier and briefly summarize the differences between each.	37	2	9	22
		128	Compare and contrast the major differences between a pore/channel and a transmembrane carrier protein and propose reasons why membranes need both.	50	0	13	7
		129	Describe and evaluate the role of ion gradients, co transporters, and ATP in active transport mechanisms.	40	0	14	16
8	**Recombinant DNA**: Student Pharmacist should be able to describe the process of molecular cloning and how it is used to express proteins for therapeutic use. Describe how molecular techniques are used to diagnose disease and how this leads to effective treatment.	130	Recombinant DNA	43	9	4	14
		131	Describe what is meant by pharmacogenomics with one or more examples.	22	0	18	30
			High:	68	12	28	52
			Low:	5	0	0	0