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Authors: Wright, Anita C., Fan, Ying, and Baker, George L.

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NUTRITIONAL VALUE AND FOOD SAFETY OF BIVALVE MOLLUSCAN SHELLFISH

ANITA C. WRIGHT, YING FAN AND GEORGE L. BAKER IV*
Department of Food Science and Human Nutrition, University of Florida, 359 FSHN Building, 572 Newell Drive, Gainesville, FL 32611-0370

ABSTRACT The Nutrient Database for Standard Reference published by the U.S.D.A. describes molluscan shellfish as an excellent source of vitamin B12, omega-3 fatty acids, choline, iron, selenium, and zinc. Edible molluscs consist primarily of mussels, clams, scallops, and oysters and are naturally low in carbohydrate, as well as total and saturated fat. With regard to omega-3 fatty acids, iron, selenium, and zinc, the nutrient value of some shellfish is superior to land-based protein sources, such as beef, chicken, and pork. Unfortunately, adverse human health considerations need to be noted because of naturally occurring pathogens, particularly *Vibrio* species, and algal toxins (brevetoxin, saxitoxin, and domoic acid) that may be present in these shellfish, as well as fecal-associated viruses (hepatitis A and norovirus) and bacteria (*Salmonella*) as a consequence of contamination of shellfish harvest sites. Other environmental contaminants (mercury, methylmercury, and polychlorinated biphenyls) may bioaccumulate in molluscan shellfish tissues as part of their filter feeding behavior and have potential health implications. Cooking molluscan shellfish greatly reduces the risk of foodborne infections and increases the nutrient value because of water loss; however, some vitamins are destroyed by cooking and natural toxins and environmental contaminants are not always eliminated by normal cooking temperatures. Coastal monitoring of water quality and postharvest processing of some products should help mitigate risks associated with shellfish consumption and promote a safer, nutrient-rich product.

KEY WORDS: food safety, minerals, molluscan shellfish, nutrition, omega-3 fatty acids, vitamins

INTRODUCTION

Commonly consumed molluscan bivalves include clams, mussels, oysters, and scallops. These commercially important species had a dockside landing value in 2015 of approximately $870 million. Although they comprise about 15% of the total seafood value in the United States, consumer preference for crustacean shellfish (shrimp comprise nearly 25% of all seafood consumed in the United States) suggests that bivalve molluscan shellfish are an underappreciated seafood commodity in the United States (NOAA 2016). In fact, seafood is the least consumed protein food overall on a weekly per capita basis in the United States. (Kantor 2016). The cost of shellfish can vary greatly but is unlikely to account for this discrepancy in consumption, as retail oyster cost ($7.99–$12.99 per pound) is comparable with beef steak ($6.99–$12.99) per pound (Bi et al. 2016). Quality and availability of molluscan shellfish can also vary widely depending on seasonality, geographic location, access to fresh seafood, and local preferences. For example, a survey conducted in 2002 in California, Florida, Louisiana, and Texas showed that 75% of all respondents reported they consumed raw oysters an average of six times in 12 mo with Louisiana as the highest (33.6%) per capita (Flattery & Bashin 2004). The Food and Drug Administration (FDA) estimates that 17.5% of the population of these four states consume raw oysters.

This review documents the unique dietary value of molluscan shellfish as a protein source that is low in calories and fat content but high in nutrients, especially vitamins that are not always found in other meats. For example, molluscan shellfish can be an excellent source of vitamin B12, choline, selenium, iron, and zinc, Furthermore, the proportion of unsaturated fatty acids in total fat is low, although being especially high in omega-3 and omega-6 fatty acids (USDA 2015). Concerns about food safety issues related to shellfish consumption are also discussed, as well as postharvest processing (PHP) and cooking preparation methods aimed at mitigation of associated risks. The primary safety consideration is related to the consumption of uncooked or raw oysters, which contain naturally occurring bacteria, namely, *Vibrio* species that are potentially pathogenic to humans. Essentially, the vast majority of reported infectious disease associated with seafood is related to consumption of raw oysters (Iwamoto et al. 2010). Molluscan shellfish can be, however, prepared in a variety of ways, including boiled, sautéed, baked, fried, broiled, and blackened, and are often found in seafood soups, stews, and sauces. They can also be canned fresh or as a processed product for longer shelf life. Human health issues related to bacterial or viral pathogens can be eliminated by simply cooking the product. Furthermore, postharvest processes, such as thermal, high hydrostatic pressure, irradiation, etc., can greatly reduce the risk of infectious disease.

Bivalve molluscs are voracious filter feeders and pump water through their gills to trap food (primarily algae) and other particulates ranging in size from 1 to 30 μm. An individual oyster is able to process at a rate of 55 L per day (Pietros & Rice 2003). Unfortunately, as a consequence of filter feeding, toxins tend to bioaccumulate (Uchida et al. 2017), and other environmental contaminants, such as mercury, methylmercury, and polychlorinated biphenyls are sometimes found in shellfish tissues with potential health implications (Venugopal & Gopakumar 2017). In the United States, shellfish harvest areas are monitored for potential biohazards, such as fecal indicator bacteria, toxic algae, and chemicals, and established protocols should ensure closure in the event of a human health threat (FDA 2011).

MACRONUTRIENTS ASSOCIATED WITH MOLLUSCAN SHELLFISH AND HUMAN HEALTH

Essential nutrients are those nutrients that are not produced by the human body in adequate amounts to sustain life and include macronutrients, such as carbohydrates, fats (fatty acids and cholesterol), proteins (amino acids), fiber, and water (USDA

*Corresponding author. E-mail: glba@ufl.edu
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2015). Other essential nutrients include vitamins and minerals. Nonessential nutrients are metabolized in the body. The following sections will address the basic roles of these essential nutrients in human health and discuss dietary resources related to molluscan shellfish. Basic nutrition facts for oysters are shown in Figure 1 and are based on a 3-oz (85 g) serving or approximately six oysters. Nutrients, vitamins, minerals, and omega-3 fatty acid levels in molluscan shellfish are summarized in Tables 1–3 and based on 100 g serving.

Water

Water is an essential nutrient in any living system. On average, an adult human body contains about 60% water. Dehydration by as little as 2% of the body weight will result in impaired physiological response (Borghi et al. 1996). Water is often involved in biochemical mechanisms and is needed to maintain body temperature. Water fills the spaces between cells, lubricates and cushions joints, and carries waste through urination, perspiration, and bowel movements (CDC 2016). Molluscan shellfish consist of approximately 75% water (USDA 2018a).

Protein

An adult male should consume 50 g of protein per day based on a 2,000-calorie diet (USDA 2018b). Protein is vital for most cellular processes and is the major component of lean muscle mass. When the body runs out of carbohydrates for energy, protein can provide the body with energy (4 kcal/g). Proteins are composed of essential and nonessential amino acids, depending on whether they are biosynthesized or obtained from the diet (Kopple 1975). Amino acids are also required as precursors for nucleic acid, enzymes, and hormones (Herman 2015). The nine essential amino acids are phenylalanine, valine, threonine, tryptophan, methionine, leucine, isoleucine, lysine, and histidine (Kopple 1975). In general, molluscan shellfish are considered to be abundant in protein and comparable with land-based protein sources (Dong 2001). For example, clams, mussels, oysters, and scallops contain 9.0%–13.0%, 12.6%–13.0%, 8.9%–14.3%, and 14.8%–17.7% protein in their raw meats, respectively (Venugopal & Gopakumar 2017). Molluscan shellfish protein is considered high-quality protein because of its essential amino acid profile and classification as a highly digestible protein source (Miletic et al. 1991).

Carbohydrates

Food carbohydrates, such as sugar, fiber, and starch, are converted to glucose to quickly supply the body with energy. However, excess carbohydrate may result in chronic health issues, such as obesity and Type 2 diabetes (Wylie-Rosett et al. 2004). As a whole, land- and aquatic-based protein sources contain little, if any, carbohydrate because muscle glycogen is depleted after an animal dies; however, molluscan shellfish contain moderate levels of carbohydrates in their tissue as they may be consumed live or shortly after death. Although molluscan shellfish are generally considered low in carbohydrate content, raw scallops, oysters, and mussels have been reported to contain between 3% and 5% carbohydrate. By contrast, carbohydrate levels in crustacean shellfish are nearly 0% in raw crab, shrimp, and lobster (USDA 2015).

Nutrition Facts
Serving Size 3 oz (85g)
Pacific Oyster, cooked dry heat

Amount Per Serving	
Calories 140	**Calories from Fat 35**
	% Daily Value*
Total Fat 4g	**6%**
Saturated Fat 1g	5%
Trans Fat 0g	
Cholesterol 85mg	**28%**
Sodium 180mg	**8%**
Total Carbohydrate 8g	**3%**
Dietary Fiber 0g	0%
Sugars 0g	
Protein 16g	
Vitamin A 8%	• Vitamin C 20%
Calcium 2%	• Iron 45%
Selenium 190%	

*Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs.

	Calories	2,000	2,500
Total Fat	Less than	65g	80g
Saturated Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg
Sodium	Less than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

Calories per gram:
Fat 9 • Carbohydrate 4 • Protein 4

Nutrition Facts
Serving Size 3 oz (85g)
Eastern Oyster, cooked dry heat

Amount Per Serving	
Calories 70	**Calories from Fat 15**
	% Daily Value*
Total Fat 2g	**3%**
Saturated Fat 0.5g	3%
Trans Fat 0g	
Cholesterol 30mg	**10%**
Sodium 140mg	**6%**
Total Carbohydrate 6g	**2%**
Dietary Fiber 0g	0%
Sugars 0g	
Protein 6g	
Vitamin A 2%	• Vitamin C 8%
Calcium 4%	• Iron 35%
Selenium 90%	

*Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs.

	Calories	2,000	2,500
Total Fat	Less than	65g	80g
Saturated Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg
Sodium	Less than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

Calories per gram:
Fat 9 • Carbohydrate 4 • Protein 4

Figure 1. Nutrition facts for cooked Pacific and eastern oysters (source: USDA National Nutrient Database for Standard Reference (2015)).

Total Fat and Saturated Fat

Fat is the main source of stored energy in the human body. Edible fats and oils occur naturally in the form of triglycerides

TABLE 1.

Selected fat, fatty acid, and cholesterol content of molluscan shellfish, beef, chicken, and pork and available dietary guidelines for 2015 to 2020.

Selected fat, fatty acid, and cholesterol content of molluscan shellfish, beef, chicken, and pork from the United States (per 100 g)	Total fat (g)	Saturated fat (g)	Polyunsaturated fat (g)	Total *trans*- (g)	18:2 (Linoleic acid) (g)	18:3 (Linolenic acid) (g)	Estimated 20:5ω3 (EPA) (g)	Estimated 22:6ω3 (DHA) (g)	Cholesterol (mg)
Clam, mixed species, raw	0.96	0.19	0.19	<dl	0.042	0.015	0.045	0.064	30
Clam, mixed, cooked, moist heat	1.95	0.19	0.55	NR	0.032	0.008	**0.138**	**0.146**	67
Clam, canned, drained solids	1.59	0.31	0.32	0.02	0.070	0.025	0.070	0.106	50
Clam, cooked, breaded, and fried	11.2*	2.68	2.87*	NR	2.445*	0.160	0.066	0.070	61
Mussel, blue, raw	2.24	0.43	0.61	NR	0.018	0.020	**0.188**	**0.253**	28
Mussel, cooked, moist heat	4.48	0.85	1.21	NR	0.036	0.040	**0.276**	**0.506**	56
Oyster, eastern, wild, raw	1.71	0.47	0.53	0.03	0.041	0.084	**0.177**	**0.136**	40
Oyster, eastern, farmed, raw	1.55	0.44	0.59	NR	0.028	0.044	**0.188**	**0.203**	25
Oyster, Pacific, raw	2.30	0.51	0.89	NR	0.032	0.032	**0.428**	**0.250**	50
Oyster, eastern, wild, cooked, moist	3.42	0.95	1.06	0.07	0.061	0.168	**0.353**	**0.271**	79
Oyster, Pacific, cooked, moist heat	4.60	1.02	1.788	NR	0.064	0.064	**0.876**	**0.500**	100
Oyster, eastern, wild, cooked, dry	2.65	0.73	0.820	0.05	0.064	0.130	**0.274**	**0.210**	62
Oyster, eastern, farmed, cooked, dry	2.12	0.68	0.713	NR	0.043	0.063	**0.229**	**0.211**	62
Oyster, eastern, breaded and fried	12.6*	3.20	3.31*	NR	2.440*	0.156	**0.202**	**0.218**	71
Oyster, eastern, canned	2.47	0.63	0.74	NR	0.049	0.037	**0.211**	**0.228**	55
Scallop, mixed species, raw	0.49	0.13	0.13	0.01	0.008	0.003	0.042	0.061	24
Scallop, mixed, cooked, steamed	0.84	0.22	0.22	0.01	0.014	0.006	0.072	0.104	41
Scallop, mixed, breaded and fried	10.9*	2.67	2.86*	NR	2.443*	0.156	0.086	0.103	54
Beef, top sirloin, steak, broiled	5.80	2.20	0.2	NR	0.169	0.016	<dl	<dl	82
Beef, ground, 70% lean, broiled	18.7	7.30	0.5	1.17	0.390	0.044	<dl	<dl	88
Chicken, breast, cooked, roasted	3.60	1.00	0.8	NR	0.590	0.030	0.010	0.020	85
Chicken, meat/Skin, fried, flour	14.9	4.10	3.4	NR	2.97*	0.150	0.010	0.050	90
Pork, fresh, loin, cooked, broiled	8.10	2.90	0.7	NR	0.650	0.020	NR	NR	94
Pork, cured, ham, boneless, cooked	7.60	1.70	0.7	NR	0.595	0.034	0.000	0.005	73
Recommended daily allowance	65–80 g per	20–25 g per					Suggested 250–500 mg		
Daily value	day	day					per day	< 300	
Adequate intake							1.6 g M/1.1 g F		

Source: USDA National Nutrient Database for Standard Reference, Release 28. The default age–sex group reference is a male age of 31–50 years based on a 2,200-calorie per day diet. <dl, below detection limit of assay; NR, not reported by USDA's full report. "Excellent sources" based on DV are displayed in bold.

* Significantly higher fat, saturated fat, and 18:2, likely because of fatty acid profile of frying oil.

consisting of three fatty acids connected to a glycerol backbone. Fat contains 9 kcal/g, which is substantially a higher energy value than that of carbohydrates or proteins (both 4 kcal/g). Although often disparaged because of its caloric value, dietary fat is essential for biological membranes, contributes to the transport and absorption of fat-soluble vitamins, and is involved with many more vital functions related to human metabolic activity. The American Heart Association recommends consuming 25%–35% of total calories from fat (AHA 2018).

By definition, saturated fats contain no double bonds in their carbon chains and are typically solid at room temperature (25°C). Most fatty acids in land-based plant and animal tissues are 16- or 18-carbon long fatty acids with zero to three double bonds. From a nutritional standpoint, the only fatty acids essential for human health are linoleic (18:2ω6) and linolenic (18:3ω3) acids because mammals lack the enzymes necessary to desaturate fatty acids beyond the C-9 position in the fatty acid's carbon chain (Berg et al. 2002). The American Heart Association (2015) suggests that the amount of saturated fatty acids in a healthy diet should not exceed 10% of total calories of your daily dietary intake and that *trans*-fatty acids should be avoided because of the risk associated with heart disease and stroke (AHA 2015).

As shown in Table 1, raw or steamed molluscan shellfish are considered low in fat (0.96–4.5 g per 100 g serving) as compared with broiled or roasted land-based meats (3.6–18.7 g). They are also notably lower in saturated fats (<1 g) compared with chicken, pork, or beef (1–7.3), although cooking methods such as breading and frying will greatly increase the fat content (USDA 2015). Fatty acid composition is also striking and comprises an abundant nutrient database for researchers to compare seafood species (Rittenschober et al. 2013). As discussed in the following paragraphs, the omega-3 fatty acids in particular are lacking in beef, pork, and poultry but are in abundant in both fish and shellfish.

Omega-3 Fatty Acids and Human Health

In the early 1980s, several studies concluded that native populations in Greenland and Japan were less susceptible to heart attacks compared with those in North America (Bang & Dyerberg 1980, Kagawa et al. 1982). It was postulated that their diet of cold water seafood, even though high in fat, was the major reason for this phenomenon. The relationship of seafood consumption to human health was further investigated over the next 20 y, as studies attempted to define the reason behind the suspected health benefits in populations that consumed mostly seafood. Results indicated that omega-3 fatty acid consumption was the main dietary contributor to increased cardiovascular health in the native population in Greenland and Japan. Further studies have indicated that omega-3 fatty acids have cardioprotective and potent anti-inflammatory effects in the human body (O'Keefe & Harris 2000).

Omega-3 fatty acids that are thought to play major roles in the human health include alpha-linolenic acid, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). To understand the nutritional implications of these omega-3 fatty acids, their chemical structure warrants explanation. The shorthand numeric fatty acid nomenclature rules describe the number of carbons in the fatty acid chain, followed by the number of double bonds in the molecule and separated by a colon (:), and then the omega-position of the first carbon from the methyl end. For example, the shorthand notation for DHA is 24:6ω3, which describes the fatty acid as having 24 carbons with six double bonds beginning at the third carbon counted from the methyl (or omega) end. Figure 2 diagrams the fatty acid nomenclature by the omega system. In addition, it is important to understand how the human body uses fatty acids. When fats are consumed as a mixture of triglycerides, pancreatic lipase liberates free fatty acids that enter the bloodstream. In different cellular compartments, mainly in microsomes, fatty acids undergo a series of elongation with carbon atoms and desaturation by double bond addition through a cascade mediated by specific metabolic elongases and desaturases that convert fatty acids in the body. The position of the first set of double bonds connected from the methyl (or ω/omega) end of the molecule remains unchanged. In other words, an omega-3 fatty acid will remain an omega-3 fatty acid of different carbon chain lengths and level of saturation after being converted in human metabolic pathways. This explains why linoleic (18:2ω6) and linolenic (18:3ω3) fatty acids are considered essential to human health. Linoleic acid undergoes carbon chain elongation and addition of double bonds to form arachadonic acid (20:4ω6), which is involved with prostaglandin and hormone formation.

Figure 3 describes the enzymatic cascade in the human body for the formation of omega-6 and omega-3 fatty acids. Unfortunately, the metabolic conversion of omega-3 fatty acids in the body is not very efficient. For example, typically less than 15% of linoleic acid (18:2ω6) is metabolically converted to DHA (22:6ω3) (NIH-ODS 2016). Therefore, direct consumption of dietary EPA and DHA are thought to have the greatest omega-3–related impact on human health. Long chain omega-3 fats, such as DHA and EPA, are thought to lower the incidence of cardiovascular disease, atrial fibrillation, telomere shortening, and metabolic syndrome in humans (Farzaneh-Far et al. 2010, Baik et al. 2010, Nielsen et al. 2012, Lund 2013). Beneficial observations related to dietary omega-3 consumption and cardiovascular disease may be due to reduced blood platelet reactivity, reduced plasma viscosity, and the reduced production of cytokines. Docosahexaenoic acid makes up approximately 90% of the omega-3 fatty acids in the gray matter of the brain (Weiser et al. 2016). The human brain consumes 20% of the body's overall energy consumption, although only weighing two percent of the average human body weight (Bradbury 2011).

Nutritionally speaking, FDA recommends adequate intake levels for dietary omega-3 fatty acids at 1.6 g for males and 1.1 g for females. Beef, chicken, and pork contain very little omega-3 fatty acids. Thus, seafood is an essential dietary source of these nutrients. The 2015–2020 United States Department of Agriculture

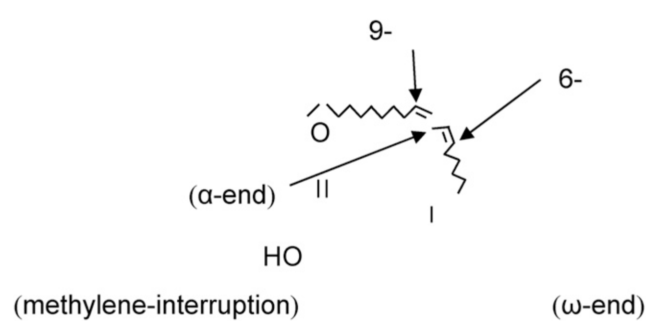

Figure 2. Diagram of the linoleic acid molecule to describe nomenclature (18:2ω6).

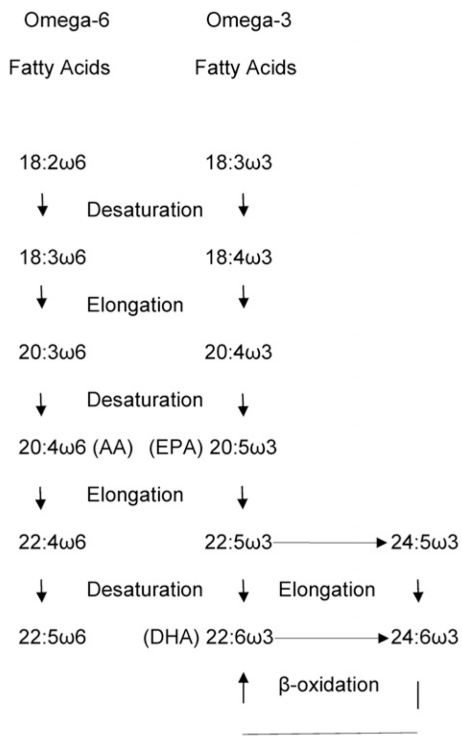

Figure 3. Elongation and desaturation of omega-6 and omega-3 fatty acids by human metabolism (adapted from Simopoulos 2016). AA, arachidonic acid.

(USDA) guidelines suggest that eight ounces (224 g) of seafood per week or 250 mg/day each of EPA and DHA (500 g total) is a sufficient amount to provide health benefits (USDA 2015). The FDA also specifies that the labels of dietary supplements should exceed a daily intake of EPA and DHA over 2 g. A 3-oz serving of salmon cooked provides about 1.6 g omega-3 fatty acids, whereas a typical 1,000 mg fish oil dietary supplement provides 180 mg EPA and 120 mg DHA (NIH-ODS 2016).

Nutritional recommendations for omega-3 consumption have focused on oily fish, but mussels and oysters can be excellent sources for total omega-3 fatty acids (Table 1). The types of fatty acid vary among species, but shellfish contain mostly EPA and DHA. Scallops contain little of omega-3 fatty acids, but oysters can exceed 500 mg for total omega-3 fatty acids.

Cholesterol

Clinical investigations over many years have linked cholesterol to heart disease and atherosclerosis (Libby et al. 2000). Recent research findings suggest that dietary cholesterol does not play as large a role in atherosclerosis as previously thought (Lecerf & de Lorgeril 2008). In addition, the human body requires cholesterol, which is found in every cell in the body and is an important precursor for many vital compounds required for the normal human body function (Simons & Ikonen 2000). For example, cholesterol is involved in the synthesis of sex hormones (estrogen and testosterone), growth, and cellular maintenance. Approximately 75% of the cholesterol in the human body at any given time is produced primarily by the body itself, in the liver, with the other 25% derived from dietary sources.

Overall, molluscan shellfish contain lower levels of cholesterol than beef, chicken, or pork (Phillips et al. 2012). Researchers have also reported that oysters and other molluscs are relatively low in cholesterol (Childs et al. 1987, Nettleton & Exler 1992). In fact, Childs et al. (1987) observed the impact of three animal proteins on cholesterol absorption in the body and discovered that males fed an oyster/clam diet showed lowered cholesterol adsorption compared with a diet of chicken meat. Eastern oysters (*Crassostrea virginica*) have slightly less cholesterol (30 mg/100 g) compared with Pacific oysters (*Crassostrea gigas*) (48 mg/100 g) (Nettleton & Exler 1992). In general, cholesterol values reported by the USDA National Nutrient Database showed that molluscs varied with preparation and were highest in steamed, followed by raw and canned at 56, 28, and 3 mg/100 g, respectively (see Table 1).

MINERALS ASSOCIATED WITH MOLLUSCAN SHELLFISH AND HUMAN HEALTH

Daily values (DV) for selected mineral content of molluscan shellfish are shown in Table 2 and are based on the Available Dietary Guidelines (2015 to 2020) from the USDA National Nutrient Database. These guidelines describe ‘‘good’’ and ‘‘excellent’’ amounts for DV, and this terminology is used in the following paragraphs to reflect these guidelines. From a dietary and U.S. regulatory perspective, recommended amounts of some nutrients, minerals, vitamins, and fatty acids have been established. A ‘‘good’’ nutritional source would contribute 10%–19% of the DV, whereas an ‘‘excellent’’ source would provide 20% or higher of a particular nutrient.

Calcium

Calcium is the most abundant metal in the human body and is essential to bone biogenesis, as deficiencies can cause osteoporosis. It is required for intracellular signaling and neural transmission. It is also an essential component of the calcium carbonate shells of molluscan shellfish and, as such, is recruited from seawater and deposited at fairly high concentrations in their tissues. Levels of calcium in shellfish are 2- to 10-fold higher than those found in beef, chicken, or pork.

Iron

The primary metabolic function of iron is the transport of oxygen throughout the body as a complex with hemoglobin and as a cofactor for electron transport (Eguchi & Saltman 1987). Iron deficiency is called anemia, and symptoms include fatigue, weakness, and difficulty maintaining body temperature (Miller 2013). Several enzymes cofactor with iron, especially for oxidative phosphorylation in the energy pathway. Dietary iron is stored in mammals primarily as a complex with ferritin, a protein complex with multiple subunits. Transferrin is the protein that transports iron within the blood where it is deposited in ferritin for storage at other locations, primarily the liver and muscles. Ascorbic acid (vitamin C) stimulates the synthesis of ferritin and the absorption of dietary iron (Hallberg et al. 1989).

United States Department of Agriculture National Nutrient Database shows that raw oysters (4.6–5.8 mg/100 g) and mussels (3.95 mg/100 g) are an excellent source of iron (Table 2). Clams (1.62 mg/100 g) contain less iron than oysters but are still a good source according to DV calculations. When cooked, the amount of available iron actually increases between 65% and 100%. For example, breaded and fried clams contain the

TABLE 2.

Selected mineral content of molluscan shellfish, beef, chicken, and pork and available dietary guidelines for 2015 to 2020.

Selected mineral content of molluscan shellfish, beef, chicken, and pork from the United States (per 100 g)	Calcium (mg)	Copper (mg)	Iron (mg)	Magnesium (mg)	Manganese (mg)	Phosphorus (mg)	Potassium (mg)	Selenium (μg)	Zinc (mg)
Clam, mixed species, raw	39.0	0.05	1.62	19.0	0.09	*198*	46.0	**30.6**	0.5
Clam, mixed, cooked, moist heat	92.0	0.69	*2.81*	18.0	**1.00**	**338**	*628*	**64.0**	*2.7*
Clam, canned, drained solids	65.0	0.09	*2.68*	32.0	0.14	**327**	*628*	**50.5**	0.8
Clam, cooked, breaded, and fried	63.0	0.36	**13.91**	14.0	**0.54**	*188*	326	**28.9**	*1.46*
Mussel, blue, raw	26.0	0.09	**3.95**	34.0	**3.40**	*197*	320	**44.8**	*1.6*
Mussel, cooked, moist heat	33.0	0.19	**6.72**	37.0	**6.80**	**285**	268	**89.6**	*2.7*
Oyster, eastern, wild, raw	59.0	2.86	**4.61**	18.0	*0.30*	97.0	156	**19.7**	**39.3**
Oyster, eastern, farmed, raw	44.0	0.74	**5.78**	33.0	*0.39*	93.0	124	**63.7**	**37.9**
Oyster, Pacific, raw	8.00	1.58	**5.11**	22.0	**0.64**	*162*	168	**77.0**	**16.6**
Oyster, eastern, wild, cooked, moist	116	5.71	**9.21**	35.0	**0.59**	*194*	139	**39.5**	**78.6**
Oyster, Pacific, cooked, moist heat	16.0	2.68	**9.20**	*44.0*	**1.22**	*243*	302	**154**	**33.2**
Oyster, eastern, wild, cooked, dry	92.0	4.44	**7.16**	28.0	**0.46**	*150*	242	**30.7**	**61.0**
Oyster, eastern, farmed, cooked, dry	56.0	1.43	**7.77**	33.0	*0.43*	115	152	**77.5**	**45.2**
Oyster, eastern, breaded and fried	62.0	4.29	**6.95**	*58.0*	**0.49**	*159*	244	**66.5**	**87.1**
Oyster, eastern, canned	45.0	4.46	**6.70**	*54.0*	**0.45**	*139*	229	**35.8**	**91.0**
Scallop, mixed species, raw	6.00	<dl	0.38	22.0	0.02	**334**	205	**12.8**	0.9
Scallop, mixed, cooked, steamed	10.0	<dl	0.58	37.0	0.03	**426**	314	**21.7**	*1.6*
Scallop, mixed, breaded and fried	42.0	0.08	0.82	*59.0*	0.14	*236*	333	**26.9**	1.06
Beef, top sirloin, steak, broiled	20.0	0.09	1.96	26.0	<dl	*244*	393.0	**35.8**	**5.7**
Beef, ground, 70% lean, broiled	25.0	0.07	2.25	19.0	<dl	*185*	275.0	**21.5**	**6.1**
Chicken, breast, cooked, roasted	15.0	0.05	1.04	29.0	<dl	*228*	256.0	**27.6**	1.0
Chicken, meat/Skin, fried, flour	17.0	0.08	1.38	25.0	<dl	*191*	234.0	**21.7**	*1.9*
Pork, fresh, loin, cooked, broiled	5.00	0.07	1.39	35.0	0.01	**290**	444.0	**47.7**	*2.9*
Pork, cured, ham, boneless, cooked	6.00	<dl	0.85	21.0	<dl	**292**	281.0	**19.8**	*2.2*
Recommended daily allowance	1,000	900	8	310		700		55	11
Daily value	1,300	900	18	420	2.3	1,250	4,700	55	15
Adequate intake					2.3		4,700.0		

Source: USDA National Nutrient Database for Standard Reference, Release 28. The default age–sex group reference is a male age of 31–50 years based on a 2,200-calorie per day diet. <dl, below detection limit of assay; NR, not reported by USDA's full report. ''Good sources'' based on DV are displayed in italics. ''Excellent sources'' based on DV are displayed in bold.

highest levels of iron reported (13.91 mg of iron per 100 g sample). Scallops (0.38 mg/100 g) contain less than half the levels of beef, chicken, and pork, whereas oysters and clams contain several times the amount for land-based meats. Farmed oyster species are reported to have slightly higher iron levels compared with wild caught, although Nettleton did not find any significant differences in farmed versus wild oysters for any nutrient they investigated (Nettleton & Exler 1992). Cooked clams and cooked beef contain similar amounts of iron.

In some individuals, a genetic abnormality results in over-absorption of iron and consequently iron overload from a condition referred to as hemochromatosis. These persons must avoid iron-rich food and may require chelation therapy or phlebotomy. Interestingly, persons with hemochromatosis are also highly susceptible to fatal *Vibrio vulnificus* disease. In mice, iron overload reduced the infectious dose from about 100,000 to theoretically one bacterium (Wright et al. 1981). Thus, consumption of raw oysters is particularly a concern to persons with hemochromatosis and should be avoided.

Magnesium

The human body contains approximately 25 g of magnesium. Magnesium is primarily found in bones and makes up 60%–65% of the total magnesium in the body (Grzebisz 2011). Approximately, 25% is involved with muscle function. As it is essential to many biochemical mechanisms in the human body, magnesium is an important metabolic mineral (Bergman et al. 2009). Magnesium is involved with nerve and muscle maintenance and function, supports immunity, healthy heart rate, and interacts with calcium in bone maintenance and keeps calcium dissolved in blood (Grzebisz 2011). Magnesium is although thought to be involved in blood glucose levels and energy production. Steamed and canned oysters provide a good source of magnesium. Fried scallops are also a good source of magnesium and contain 18 to 58 mg/100 g, while other molluscan shellfish ranged from 14 to 37 mg/100 g.

Manganese

Manganese is involved in enzyme function and is even a component of several enzymes, such as arginase, concanavalin A, glutamine-synthase, and many others (Horning et al. 2015). There appears to be a number of roles that manganese plays in osteoporosis, diabetes, and seizure disorders. In addition, toxic levels of manganese in water have also been reported. The U.S. Environmental Protection Agency has a 50 μg/L maximum allowable level of magnesium in drinking water (EPA 2018b). Manganese toxicity may result in moderate to severe neurological symptoms to those similar to Parkinson's disease

(Aschner et al. 2009). Clams, cooked oysters, and mussels are either a good or excellent source of dietary manganese. Raw Pacific oysters and cooked eastern oysters vary between being ranked good to excellent sources of manganese. Canned clams contain moderately low levels of manganese.

Phosphorus

Phosphorus is necessary as an essential mineral that is primarily used for growth and repair of human cells and tissues, as well as healthy energy levels (Bergman et al. 2009, Kraft 2015). Approximately 85% of all the phosphorus in the body is a hydroxyapatite complex with calcium, which is responsible for bone hardness (Bergman et al. 2009). Vitamin D is required to absorb phosphorus efficiently by acting as a cofactor for several human metabolic functions. Nearly all clams, mussels, and scallops are a good to excellent source of phosphorus. Raw and steamed scallops are excellent sources of phosphorus. Phosphorus levels are highest in steamed scallops, but clams and mussels cooked by moist heat also contain excellent sources of phosphorus. Most molluscan shellfish evaluated in this review are a good source of phosphorus, as are nearly all land-based animals. Pork is an excellent source of phosphorus, but higher phosphorus values are found in clams and scallops.

Potassium

Potassium is involved in muscle contraction, healthy blood pressure, fluid balance in cells, and bone longevity, in addition to several factors associated with nerve and heart health. In 2015, the Dietary Guidelines Advisory Committee proposed changes to the nutrition facts panel because less than three percent of the U.S. population consumes enough potassium (USDA 2015). Clams are naturally high in potassium. In nearly all cases, they are more than double the concentration of other molluscan shellfish.

Selenium

Selenium works as an antioxidant in the human body and has known synergistic effects with vitamin E (Bourre & Paquotte 2008). Several studies conducted throughout the world strongly suggest that free selenium sequesters elemental mercury, thus reducing biological availability of elemental mercury in humans and fish (Sormo et al. 2011, De et al. 2014). Mercury has no known role in biological systems and can become concentrated in aquatic environments (Olmedo et al. 2013b, Gribble et al. 2016). A recent study from Morris et al. (2016) showed a positive correlation between seafood consumption and mercury levels in the brain; however, there was no relationship between higher concentrations of mercury in the brain and brain neuropathology. Furthermore, seafood consumption correlated with lower neuritic plaques associated with Alzheimer's disease.

The amount of dietary selenium is high in clams and mussels and is similar to that found in beef, chicken, and pork; however, oysters show a greater range of selenium (19–154 mg), whereas scallops were generally below the recommended daily allowance (55 mg). The highest selenium levels reported comes from mussels cooked in moist heat. Raw and steamed scallops are also excellent sources of selenium.

Zinc

Zinc is a major contributor to health and nutrition by boosting immune function, regulation of aging, atherosclerosis, and autoimmune diseases (Samman 2007). There may also be other roles zinc plays in cancer, diabetes, Alzheimer's disease, and other age-related conditions (Choy et al. 2002, Samman 2007, Sandstead 2012, Guan et al. 2015, Maulvault et al. 2015). Oysters are very high in zinc. Fresh and canned mussels contained the highest samples of zinc in a study conducted by Olmedo et al. (2013a). United States Department of Agriculture (Table 2) reported that the zinc concentration in canned eastern oysters is 91 mg per 100 g of sample, which is 500 times more than the DV for zinc.

VITAMINS ASSOCIATED WITH MOLLUSCAN SHELLFISH AND HUMAN HEALTH

Daily values for selected vitamin content of molluscan shellfish are shown in Table 3 and are based on the Available Dietary Guidelines (2015 to 2020) from the USDA National Nutrient Database. These guidelines describe "good" and "excellent" amounts for DV, and this terminology is used in the following paragraphs to reflect these guidelines. A "good" nutritional source would contribute 10%–19% of the DV, whereas an "excellent" source would provide 20% or higher of a particular nutrient.

Vitamin C (Ascorbic Acid)

Vitamin C functions as an antioxidant and is involved with cellular repair, production of neurotransmitters, and immune function. It is a cofactor in enzymatic reactions and is found in a wide variety of foods (Prunty & Vass 1943, Brin 1982). Clams, oysters, and mussels cooked in moist heat are a good source of vitamin C.

Vitamin B1 (Thiamine)

Vitamin B1 is associated with energy metabolism, the pentose phosphate cycle as a coenzyme (thiamin diphosphate), and deficiency may contribute to infertility (Tsuji et al. 2017). Raw clams, clams, and Pacific oysters cooked under moist heat, mussels, and oysters, either farmed and cooked by dry heat, fried, or canned, contain good amounts of vitamin B1. Steamed mussels show the highest values listed of vitamin B1 with 0.3 mg/100 g.

Vitamin B2 (Riboflavin)

The coenzymes that vitamin B2 forms play major roles in energy metabolism, cellular function, and the metabolism of fat (Bacher et al. 2000). These cofactors are involved with flavoprotein enzyme reactions and includes the activation of other vitamins (NIH-ODS 2018a). Clams, mussels, and oysters cooked under moist heat show that vitamin B2 is an excellent dietary source. Raw oysters and mussels can also be a good or excellent dietary source of vitamin B2.

Vitamin B3 (Niacin)

Nicotinamide, NAD, and NADP makes up the vitamin B3 complex that is involved in a litany of metabolic processes.

TABLE 3.

Selected vitamin content of molluscan shellfish, beef, chicken, and pork and available dietary guidelines for 2015 to 2020.

Selected vitamin content of molluscan shellfish, beef, chicken, and pork from the United States (per 100 g)	Vitamin C (mg)	Vitamin B1 (mg)	Vitamin B2 (mg)	Vitamin B3 (mg)	Vitamin B5 (mg)	Vitamin B6 (mg)	Vitamin B12 (μg)	Folate (μg)	Choline (mg)
Clam, mixed species, raw	0.00	*0.02*	0.04	0.35	0.15	0.01	**11.3**	5.00	*65.0*
Clam, mixed, cooked, moist heat	221	*0.15*	**0.43**	**3.35**	0.68	0.11	**98.9**	29.0	NR
Clam, canned, drained solids	0.00	*0.02*	0.07	0.58	0.25	0.02	**18.6**	7.00	**107**
Clam, cooked, breaded and fried	10.0	0.10	*0.24*	**2.06**	0.43	0.06	**40.3**	18.0	NR
Mussel, blue, raw	8.00	*0.16*	*0.21*	**1.60**	0.50	0.05	**12.0**	*42.0*	*65.0*
Mussel, cooked, moist heat	*13.6*	**0.30**	**0.42**	**3.00**	0.95	0.10	**24.0**	**76.0**	NR
Oyster, eastern, wild, raw	<dl	0.02	0.09	0.93	0.22	<dl	8.75	0.02	*65.0*
Oyster, eastern, farmed, raw	4.70	0.11	0.07	1.27	0.16	0.06	16.2	0.02	NR
Oyster, Pacific, raw	8.00	0.07	*0.23*	*2.01*	0.50	0.05	16.0	0.01	NR
Oyster, eastern, wild, cooked, moist	<dl	0.04	*0.18*	*1.85*	0.45	0.06	17.5	0.01	**130**
Oyster, Pacific, cooked, moist heat	*12.8*	*0.13*	**0.44**	**3.62**	0.90	0.09	28.8	0.02	NR
Oyster, eastern, wild, cooked, dry	<dl	0.03	0.11	1.37	0.35	0.05	**12.9**	0.01	*101*
Oyster, eastern, farmed, cooked, dry	6.00	*0.13*	0.06	1.79	0.20	0.08	**16.2**	0.02	NR
Oyster, eastern, breaded and fried	3.80	*0.15*	*0.20*	1.65	0.27	0.06	**15.6**	0.01	NR
Oyster, eastern, canned	5.00	*0.15*	*0.17*	1.24	0.18	0.10	**19.1**	0.01	*81.0*
Scallop, mixed species, raw	0.00	0.01	0.02	0.70	0.22	0.07	*1.41*	16.0	*65.0*
Scallop, mixed, cooked, steamed	0.00	0.01	0.02	1.08	0.37	0.11	*2.15*	20.0	**111**
Scallop, mixed, breaded and fried	2.30	0.04	0.11	1.51	0.20	0.14	*1.32*	18.0	NR
Beef, top sirloin, steak, broiled	<dl	<dl	<dl	**8.74**	0.60	0.66	1.71	10.0	**116**
Beef, ground, 70% lean, broiled	<dl	<dl	0.18	**4.54**	0.66	0.34	2.90	11.0	*77.8*
Chicken, breast, cooked, roasted	<dl	0.07	0.11	**13.70**	0.97	0.60	N	4.00	*85.3*
Chicken, meat/Skin, fried, flour	<dl	0.09	0.19	**8.99**	1.08	0.41	0.31	9.00	*79.8*
Pork, fresh, loin, cooked, broiled	1.0	0.97	0.38	**5.05**	0.90	0.52	0.98	6.00	NR
Pork, cured, ham, boneless, cooked	23.3	0.53	0.24	**3.55**	0.87	0.26	1.41	3.00	NR
Recommended daily allowance	90.0	1.20	1.30	16.0		1.30	2.40	400	
Daily value	90.0	1.20	1.30	16.0	5.00	1.70	2.40	400	550
Adequate intake									550

Source: USDA National Nutrient Database for Standard Reference, Release 28. The default age–sex group reference is a male age of 31–50 years based on a 2,200-calorie per day diet. <dl, below detection limit of assay; NR, not reported by USDA's full report. ''Good sources'' based on DV are displayed in italics. ''Excellent sources'' based on DV are displayed in bold.

Vitamin B3 deficiency can cause nausea, skin and mouth lesions, anemia, headaches, and lack of energy (USNLM 2018b). Cooked clams, steamed oysters, and cooked mussels are excellent sources of vitamin B3; however, its levels are much lower than in beef, chicken, and pork. For example, roasted chicken contains approximately 280% more vitamin B3 than the highest value for molluscan shellfish (steamed Pacific oysters).

Vitamin B12 (Cobalamins)

Vitamin B12 is a water-soluble vitamin that is especially important in DNA synthesis and regulation (Ryan-Harshman & Aldoori 2008). It is required for proper red blood cell function, promotes a healthy neurological system, and plays a role in fatty acid metabolism (NIH-ODS 2018b). Amino acid metabolism is also mediated by vitamin B12. Clams and mussels are excellent sources of vitamin B12. Steamed clams contain 98.9 μg of vitamin B12, which is more than double the next highest level in fried clams. Oysters and scallops also provide a good source of vitamin B12.

Folate/Folic Acid

Folate is a water-soluble B vitamin that is either naturally present (particularly in leafy greens) and/or fortified in some foods (NIH-ODS 2018c). Folate is a coenzyme of single carbon in nucleic acid synthesis and the metabolism of amino acids. It is especially important in the conversion of homocysteine to methionine in the synthesis of methyl donor, S-adenosylmethionine (Bailey et al. 2001). Raw mussels are the only good source of dietary folate among molluscs, whereas oysters are notably lacking in this nutrient (0.1–0.2 mg/100 g). Steamed mussels contain almost double the concentration of folate found in raw mussels (76 and 42 mg/100 g, respectively). In comparison, land-based proteins range from 3 to 11 mg/100 g.

Choline

Choline is considered an essential micronutrient and is vital for early brain development. It is found in cell membranes as part of the headgroup of phospholipids. Although small amounts of choline are produced in the liver as phosphatidylcholine, choline must be obtained from the diet to meet human requirements (Ziesel & da Costa 2009). It is also the precursor for acetylcholine, an important neurotransmitter involved in memory function and movement and supports cellular methylation reactions, including genomic methylation (Wallace & Fulgoni 2017). Dietary choline levels tend to be high in canned clams and oysters cooked under dry heat. Chicken and beef contain good or excellent levels of dietary choline. The choline content of oysters and clams are comparable with that of beef and chicken.

MOLLUSCAN SHELLFISH AND SEAFOOD SAFETY

Although nutritional benefits related to consumption of molluscan shellfish are clearly evident, there are food safety considerations related to these seafood products, particularly when consumed raw. Filter-feeding molluscs can concentrate pathogens and toxins that are detrimental to human health. Seafood is responsible overall for less than 7% of illnesses or deaths from foodborne outbreaks in the United States. (Painter et al. 2013). These data excluded *Vibrio vulnificus*, which is the leading cause of death from infectious disease related to seafood consumption; however, the incidence of disease is rare (124 cases in 2014) relative to *Salmonella* (>million cases/year) https://www.cdc.gov/nationalsurveillance/pdfs/covis-annual-summary-2014-508c.pdf.

Seafood safety concerns are largely related to risks associated with the consumption of raw shellfish. Many of these risks could be avoided simply by cooking the product; however, a culture of consuming oysters raw dates back to early human populations, as evidenced by the discovery of massive shell middens that are an archaeological testament to raw oyster consumption. These mounds of mollusc shells are generally located either nearshore or underwater and are thought to be directly associated with molluscan shellfish consumption in villages along coastal areas. Molluscan shellfish were both a food source and a useful tool, as shell by-product was used for cutting and digging applications (Smith 2015).

Vibrio Species

Most of the infectious agents associated with molluscan shellfish safety are naturally occurring in the estuarine and marine environment, although pathogens can be transmitted through fecal sources of contamination. *Vibrio* species are the primary indigenous pathogens and account for 75% of seafood-related infectious disease (Scallan et al. 2011). Vibrios are present ubiquitously in coastal habitats and comprise the natural microflora of shellfish. Risk of *Vibrio*-related diseases has been shown to increase greatly with warming water temperature, as cases are more prevalent in summer months. Also, warming of coastal waters due to climate change is likely to contribute to increased disease incidence (Vezzulli et al. 2012).

The majority of foodborne vibriosis in the United States is attributed to *Vibrio parahaemolyticus*, accounting for 45% or 54% of cases from 1996 to 2010 based on COVIS or FoodNet, respectively (Newton et al. 2012). This bacterium generally causes a mild diarrhea but is frequently associated with large outbreaks of disease. CDC estimates 128 cases are not reported for every confirmed illness; thus, this organism is largely responsible for the estimated 80,000 cases/year of *Vibrio* infections in the United States of which 65% are thought to be foodborne. Disease incidence varies from year to year but is most common in the Pacific northwest and North Atlantic states, and *V. parahaemolyticus* monitoring programs have been used for disease prediction and guidance for harvest closure in some areas.

The second most common cause of vibriosis in the United States is *Vibrio vulnificus*, which produces a much more serious disease that frequently becomes systemic and can be rapidly fatal. Although this organism is responsible for only 19% or 13% of infections, depending on the reporting source, it causes greater than 80% of mortality associated with seafood (Newton et al. 2012). Diarrheal symptoms are rare, but overwhelming sepsis may follow ingestion of seafood or wound infections that can be fatal within 48 h. The vast majority of persons with foodborne *V. vulnificus* disease have ingested raw oysters and have some type of underlying condition, such as hemochromatosis (iron overload), liver disease, diabetes, and AIDS. These persons should avoid consumption of raw oysters and also exposure of open wounds to seawater, fish, or shellfish, as their fatality rate exceeds 50% for infected individuals.

Vibrio alginolyticus is the third most common cause of vibriosis is the United States. Although this species is considered an emerging foodborne pathogen, it is more commonly implicated in wound and ear infections. Symptoms include gastroenteritis and occasionally septic shock. Other *Vibrio* spp. associated with consumption of raw shellfish include *Vibrio cholerae*, but cases are rare and mostly sporadic, although a small outbreak ($n = 11$) attributed to consumption of raw oysters was reported in 2011 (Onifade et al. 2011).

Other Bacterial and Viral Pathogens Associated with Seafood

Salmonella enterica infections have been associated with molluscan shellfish consumption, and a survey of oysters harvested from 36 bays in the United States found that 7.4% harbored the bacterium, primarily from the serogroup Newport (78%) (Brands et al. 2005). Furthermore, an FDA market survey (DePaola et al. 2010) detected *Salmonella* in oyster products (1.5%), and this survey also reported the prevalence of two viruses most often associated with disease related to shellfish consumption, namely, norovirus (3.9%) and hepatitis A virus (4.4%) (Rippey 1994).

Toxic Algae

Toxic algal blooms present a challenge to the seafood industry and are particularly concerning for consumption of filter-feeding molluscan shellfish that may accumulate these toxins (Basti et al. 2018). The primary toxic species are dinoflagellates, which are classified by their toxic repertoire and include neurotoxic shellfish poisoning (*Karenia brevis*), paralytic shellfish poisoning (mixed species, including *Alexandrium* spp.), and diarrhetic shellfish poisoning (*Dinophysis* and *Prorocentrum* species). Symptoms range from mild diarrhea to serious neurological complications, such as mouth tingling, slurred speech, respiratory distress, and paralysis. Species of the diatom *Pseudo-nitzschia* cause amnesic shellfish poisoning, which can produce short-term memory loss. The ciguatera toxin-producing *Gambierdiscus* spp. are more likely associated with fish poisoning from consumption of large fish high in the food chain than they are with shellfish poisoning.

Mercury Poisoning

Coal-burning power plants are a dominant source of human-caused mercury emissions in the atmosphere and account for ~40% of domestic (5% global) mercury emissions in United States, remaining as either deposited in the soil and water (25%) or as a component of the global biogeochemical cycle (75%) (EPA 2018a). Marine bacteria (*Pseudomonas* spp.) convert elemental mercury to methylmercury in aquatic environments (Blackmore & Wang 2004, De et al. 2007). As a result, most common organic mercury compound found in the environment is a methyl mercury–cysteine complex (Berry & Ralston 2008). Several investigators have researched selenium's role in binding heavy metals (especially mercury), potentially reducing toxicity (Cuvin-Aralar & Furness 1991). Also, selenium compounds, particularly selenium P, bind mercury to decrease toxicity (Cuvin-Aralar & Furness 1991, Yoneda & Suzuki 1997, Chapman & Chan 2000, Raymond 2004, Ralston et al. 2008); however, severe mercury poisoning after bioaccumulation of mercury in molluscan shellfish and finfish from dumping of industrial wastewater may expose pregnant women to mercury or methylmercury and could impact the health of the fetus (Wooltorton 2002), as there is no effective treatment for methylmercury exposure. A recent advisory by the FDA suggests that women of childbearing age, especially if breastfeeding or pregnant, eat two to three servings of fish per week from the "best choices list" (FDA 2017a), which includes clams, oysters, and scallops, whereas mussels are not listed in the advisement document.

Shellfish Safety Monitoring

In general, safety of shellfish in the United States is monitored at harvest and is based on water quality standards determined by the FDA and the Intestate Shellfish Sanitation Conference (www.issc.org/home) and described in the National Shellfish Safety Program Guide (NSSP 2015). Coastal states in the United States track fecal indicator bacterial (fecal coliforms or *Escherichia coli*) to determine open and closing of harvest areas. Heavy rainfall can cause nonpoint source pollution and may instigate closures. California now monitors *Vibrio parahaemolyticus* levels that indicate increased risk and precipitate cessation of shellfish harvesting. Some states also monitor directly for toxic algal species. For example, Florida Department of Environmental Protection does periodic sampling for algal species and maintains a hot line for reporting blooms (https://floridadep.gov/dear/algal-bloom/content/algal-bloom-sampling-results).

Health considerations for *Vibrio vulnificus* are not addressed by monitoring, as the organism is found naturally in coastal waters and is not a result of fecal contamination. The presence of *V. vulnificus* (or other pathogens) does not change the sensory attributes of molluscan shellfish, as these are not spoilage organisms and would be essentially impossible to detect even in an oyster with high levels of *Vibrio* spp. by visual inspection, taste, or smell (Mouzin et al. 1997). Bacterial and viral contamination of both raw and cooked seafood during PHP or storage have been reported and also present risks that are not prevented by the current system of monitoring (Baker 2016).

It appears that most of the general public understands that there is a certain level of risk when raw oysters are consumed, but a survey conducted by the ISSC in 2002 noted that there were several health risks that were not well known to raw oyster consumers with certain underlying medical conditions, such as diabetes. In addition, some raw oyster consumers have the general knowledge that oysters may collect and concentrate bacteria and virus particles naturally because of the way they feed (Uchida et al. 2017). Warnings on menus serving raw fish and shellfish draw attention to these risks and have been validated by successful lawsuits against seafood restaurants that ensure labels are informative and visible; however, it should be noted that unlike other food industry, shellfish suppliers and retailers have long maintained a tracking system that tags the location and harvest date for all oysters to facilitate trace-back investigations and prevent large outbreaks (Wright et al. 2009, NSSP 2015).

Post-Harvest Processing

To address problems associated with the consumption of raw molluscan shellfish, the National Shellfish Sanitation Program promoted and, in some cases, mandated harvest time–temperature controls, specific storage parameters, and PHP methods to reduce the food safety risk. This information is provided in detail at the website for the Interstate Shellfish Sanitation Conference (http://www.issc.org/). One method commonly used in Europe is depuration or wet storage using sanitized seawater to "flush" out filter-feeding shellfish (NSSP 2015). Although this method is effective in removing fecal-associated bacteria, *Vibrio* spp. are not eliminated. PHP methods now in practice in the United States include thermal processing, freezing, irradiation, and high hydrostatic pressure (Wright et al. 2009, Wright & Schneider 2010). These methods are generally effective and will reduce levels of *Vibrio* spp. to the required nondetectable level; however, they all have the disadvantage of killing the mollusc, and thus require additional storage and packaging protocols for the product to be served as a "on the half shell."

Alternatively, shellstock can be transferred from estuaries with relatively low salinity (1–10 ppt) and high *Vibrio* levels to more off-shore sites with higher salinity and lower *Vibrio* levels. The process is called relaying and has been shown to be effective in some cases but may not be suitable for all *Vibrio* species, as some (*Vibrio parahaemolyticus* in particular) has higher salinity tolerance. If PHP is used to reduce human pathogens in molluscan shellfish, the dealer must use the process under a seafood hazard analysis critical control point plan and validate that it achieves a minimum 3.52 log reduction of viable bacteria and reduces the level of *Vibrio vulnificus* and *V. parahaemolyticus* to nondetectable levels (Baker 2016). A novel method using a derivative of chitin in the form of chitosan microparticles was recently described (Fang et al. 2015) and was effective against all the three major pathogenic *Vibrio* species to achieve the required reductions while leaving the oyster viable; however, efficacy of chitosan for *Salmonella* was inhibited in the presence of sea salt (Fan et al. 2017).

Molluscan Shellfish and Cooking

Fried and steamed oysters are commonly consumed in the United States, but raw remains the number one method of consumption (Flattery & Bashin 2004). In other countries and cultures, clams, mussels, and scallop meats are also frequently consumed raw. In the United States, clams, mussels, and scallops are mostly prepared by sautéing, frying, broiling, and incorporated in a soup or chowder. The USDA Nutrient Database for raw oysters, clams, mussels, and scallops (Tables 1–3) compares raw versus preparation by several cooking and/or preservation methods. The nutritional content for cooked food appears to increase after cooking because of water loss. Cooked seafood will lose some level of moisture (even if steamed or boiled), resulting in nutrient concentration effects unless thermal degradation or loss from edible tissue. Some B vitamins are particularly heat labile (Nettleton & Exler 1992). Domingo (2016) studied common cooking procedures and their effect on levels of environmental contaminants. Results suggest that common cooking methods (boiling, frying, grilling, and roasting) may reduce the level of organic contaminants in the cooked product because these residues are present in fatty tissues that melt during cooking and thus are not consumed.

FDA (2017b) described guidelines for cooking molluscan shellfish to ensure food safety. Unless previously processed, shellfish are sold live and should be examined before cooking for open shells that do not close, as product with open shells are likely dead. Dead shellfish decompose rapidly, increasing the likelihood of contamination with pathogenic bacteria. To boil molluscan shellfish in the shell, cook until the shells are open and continue boiling for five more minutes. When steaming, do so until the shells open, then continue for an additional 10 min. If the shellfish do not open during cooking, do not eat them as they may have been dead or injured before cooking. If the oyster meat is already shucked from the shell, boil for at least 3 min or until the edges begin to curl. Deep-fat frying of shucked oysters (whether breaded or not) should be at an oil temperature of 375°F/190°C. Shucked oysters can also be broiled when the heating sources is approximately 3 inches from the top of the oyster for at least 3 min.

Some health-related considerations from consuming fried molluscs include increasing the fat concentration from oil uptake in the muscle tissue. Also, most fried foods are breaded which increases carbohydrates, calories, and additional frying oil uptake. Furthermore, frying oil can become oxidized after sufficient use, and oxidized fat consumption is also associated with negative health implications due to formation of toxic aldehydes (Viau et al. 2016). Soybean oil, canola oil, or frying oil blends, commonly used for frying seafood, are also subject to auto-oxidation after if improperly stored. Volatile off-flavors are formed because of accelerated oxidative rancidity during repeated frying that forms aldehydes, ketones, alcohols, carboxylic acids, and other organic compounds which are associated with fishy, painty, cardboardy, green, grassy, and many other off-flavors (Kinsella 1987). There are several positive aspects to frying foods, as it introduces additional flavors, reduces moisture, changes in texture, and eliminates pathogenic bacteria. A restaurant or food processor commonly change the oil enough to minimize any off-flavors that come from the frying process. It is also unlikely that toxic levels of aldehydes would not be consumed at high enough concentrations to have health implications because the consumer would likely not eat it because of the rancid flavor of the fried seafood.

CONCLUSIONS

Molluscan shellfish, such as oysters, clams, mussels, and scallops, provide an excellent dietary source of various health-related nutrients that may not be available in land-based protein sources. The commonly consumed products are naturally low in fat, saturated fat, and cholesterol, whle providing adequate amounts of heart-healthy omega-3 fatty acids at levels that meet suggested daily intake amounts. Frequent consumption of raw or cooked shellfish, particularly oysters and mussels, provides a diet that is rich in EPA and DHA and exceeds levels found in beef, chicken, and pork by 200%.

Health benefits or other attributes that are thought to be obtained from eating raw, as compared with cooked, molluscan shellfish need to be balanced by potential risks, particularly for individuals with immune deficiency or iron overload conditions that increase susceptibility to fatal *Vibrio vulnificus* disease. Cooking essentially eliminates the risk of infectious diseases associated with consumption of raw seafood and increases the nutrient composition by virtue of water loss. Although marine toxins common to molluscan shellfish will not likely be denatured at normal cooking temperatures, water quality monitoring by state regulatory agencies reduces the potential risk for human exposure by mandating closure for suspect harvest areas. In addition, molluscan shellfish suppliers can use post-harvest techniques to lower the risk of harmful bacteria, toxins, or heavy metals (Greig & Wenzloff 1978, Anacleto et al. 2015, Baker 2016). Finally, the risk to healthy individuals from consuming cooked molluscan shellfish is extremely low, whereas nutritional benefits are uniquely abundant, especially for essential nutrients that should promote good health. Bon appétit!

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