

An estimate of the cost of acute health effects from food- and water-borne marine pathogens and toxins in the USA

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ABSTRACT

Large and growing segments of the United States population consume seafood or engage in marine recreation. These activities provide significant benefits but also bring risk of exposure to marine-borne illness. To manage these risks, it is important to understand the incidence and cost of marine-borne disease. We review the literature and surveillance/monitoring data to determine the annual incidence of disease and health consequences due to marine-borne pathogens from seafood consumption and beach recreation in the USA. Using this data, we employ a cost-of-illness model to estimate economic impacts. Our results suggest that health consequences due to marine-borne pathogens in the USA have annual costs on the order of US\$900 million. This includes US\$350 million due to pathogens and marine toxins specifically identified as causing food-borne disease, an estimated US\$300 million due to seafood-borne disease with unknown etiology, US\$30 million from direct exposure to the *Vibrio* species, and US\$300 million due to gastrointestinal illness from beach recreation. Although there is considerable uncertainty about the degree of underreporting of certain pathogen-specific acute marine-related illnesses, the conservative assumptions we have used in constructing our estimate suggest that it should be considered a lower bound on true costs.

Key words | contaminated beach exposure, cost-of-illness model, health costs, marine-borne disease, seafood-borne illness, underreporting

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ABBREVIATIONS

ADA	American Diabetes Association	NRC	National Research Council
ASP	amnesiac shellfish poisoning	NSP	neurotoxic shellfish poisoning
CDC	Centers for Disease Control and Prevention	PSP	paralytic shellfish poisoning
CFP	ciguatera fish poisoning	USDA	United States Department of Agriculture
CSPI	Center for Science in the Public Interest		
COVIS	Cholera and Other <i>Vibrio</i> Illness Surveillance System		
EPA	Environmental Protection Agency		
ERS	Economic Research Service		
ERSD	end-stage renal disease		
FoodNET	Foodborne Disease Active Surveillance		
HAB	harmful algal blooms		
HUS	hemolytic uremic syndrome		
NNDSS	National Notifiable Disease Surveillance System		

INTRODUCTION

The marine environment contains millions of microbial pathogens and toxins that are both naturally occurring and foreign; and many of these microbial agents have been linked to human diseases (Thompson *et al.* 2005). As coastal urban communities grow and our reliance on marine environments for aquaculture and recreation increases, so

do the risks of disease from these pathogens. The primary goal of this study is to produce an estimate of the annual human health costs for residents of the USA due to exposure to selected pathogens and toxins from the marine environment. This estimate will allow researchers and public health officials to target pathogens with the greatest economic impact to public health, and may lead to improvements in monitoring of marine waters by producing an economically optimal management strategy. We also identify areas for further research to develop a more complete economic analysis.

The pathogen-specific cost estimate in this paper includes two viral pathogens, 15 bacterial pathogens, and four marine toxins. Many of these pathogens and toxins are endemic to the marine environment (e.g. the *Vibrio* species); others enter the water via fecal contamination (e.g. Norwalk virus, *Salmonella* and *Campylobacter*). Over the past 15 years, about 9% of seafood-related outbreaks with known etiology were caused by viruses (predominately Norwalk virus), 25% were caused by bacteria and 64% were from marine toxins (CSPI 2007).

The pathogens selected for this analysis are those for which there is evidence of links to human disease, with documented cases in the USA. Seafood is thought to be the most common route of exposure, although this may depend in part on the limited data on illnesses due to direct exposure and the lack of reliable methods for detecting specific pathogens in marine waters. Our approach excludes marine agents for which there is too little surveillance to obtain accurate measurements, such as parasites, anthropogenic chemical agents, persistent organic pollutants, heavy metals and pharmaceutically active products. Potential chronic health effects due to these agents may contribute significantly to health costs (AMAP 1998; Judd *et al.* 2004; McDonald & Reimer 2008).

The two primary routes of transmission for marine-borne disease are seafood consumption and direct exposure from beach recreational environments. Direct exposure includes accidental ingestion of contaminated water, exposure to skin, eyes and ears during swimming and the inhalation of aerosolized toxins while at the beach. The methods used to estimate disease incidence and cost are different for each route of transmission, largely because of differences in case reporting and pathogen identification.

Seafood is a leading cause of food-borne disease with known etiology, responsible for 10–20% of outbreaks (two or more cases caused by the same source) among all food types and about 5% of all individual illnesses (Huss *et al.* 2004; CSPI 2007). The Centers for Disease Control and Prevention (CDC) is the agency primarily responsible for tracking and monitoring food-borne disease, and maintains several surveillance systems that are the basis for incidence and cost estimates of seafood-borne illness. The limitations of underreporting and unknown etiology in these data systems must be considered in interpreting the reported figures and calculating cost and incidence estimates.

Most surveillance systems record only 1–10% of food-borne cases (CDC 1988; Huss *et al.* 2004) because in many of these cases medical help is not sought. Illnesses with mild symptoms (such as that caused by Norwalk virus) or those endemic to particular regions and thus familiar to local residents [such as ciguatera fish poisoning (CFP) in the tropics] are more likely to go unreported. The reporting rate also depends on whether the surveillance system relies on health care providers to report a disease (passive surveillance) or if regular outreach to laboratories and hospitals encourages reporting (active surveillance).

Even when help is sought by the patient, health care professionals may either misdiagnose or fail to recognize the illness as marine borne, may not report the illness to public health officials, or may not obtain specimens for diagnosis. When specimens are available, laboratories are not always able to perform the necessary diagnostic tests. The lack of diagnostic techniques often makes it impossible to identify the pathogenic etiology (Olsen *et al.* 2000). In 1998 improvements in the laboratory method for detection of Norwalk virus resulted in increases in seafood-borne disease attributed to Norwalk (CSPI 2007). Prior to the change in methodology, few cases of seafood-borne illness were attributed to Norwalk virus. A recent study has shown that *Staphylococcus aureus*, including MRSA (methicillin-resistant *S. aureus*) and MSSA (methicillin-sensitive *S. aureus*), has been found in recreational marine environments from bather shedding (Plano *et al.* 2011). Given the high number of *S. aureus* infections in hospitals (McCaig *et al.* 2006; Moran *et al.* 2006) and number of deaths due to this bacteria (Klein *et al.* 2007), inclusion of

these illnesses could significantly increase the cost estimate of marine-borne illness.

While the incidence of seafood-borne disease is largely estimated from surveillance data, illnesses from direct exposure are estimated primarily using modeling techniques. An exception is the Cholera and Other *Vibrio* Illness Surveillance (COVIS) system established in 1988 to record the number of illnesses from exposure to the bacterial *Vibrio* species. Although most *Vibrio* infections result from ingestion of contaminated seafood, 12–28% are from direct exposure to marine water (CDC 1999–2006) resulting in wound infections (Shapiro *et al.* 1998).

Most incidence estimates for disease from direct exposure model the number of excess cases of gastrointestinal illness using risk relationships between polluted water and illness. These relationships are derived from randomized trial studies (Fleisher *et al.* 1996) and prospective cohort studies (Cabelli *et al.* 1982), and show that swimmers exposed to high levels of fecal indicator bacteria experienced adverse health symptoms including gastrointestinal illness (Cabelli *et al.* 1982; Haile *et al.* 1999), respiratory illness and infections in the eyes, ears and skin (Fleisher *et al.* 1998, 2010).

Using these relationships and an exposure index based on *Enterococcus* levels and swimming exposure, Given *et al.* (2006) estimated an excess 627,800–1,479,200 cases of gastrointestinal illnesses at 28 beaches in Southern California, with an economic loss of US\$21–51 million. Similarly, 36,778 excess cases of gastrointestinal illnesses per year were found at two beaches in Southern California, resulting in a \$3.3 million loss (Turbow *et al.* 2003). Although these studies were limited to a small region where recreational beach attendance is high, it is likely that public health costs exist at other recreational beaches around the country.

The adverse effect of ocean exposure on health outcomes is not limited to fecally contaminated waters. Aerosolized brevetoxins produced by the marine algae *Karenia brevis* have been associated with respiratory symptoms among asthmatics on beaches in Southern Florida. Studies have found a significant increase in intensity of respiratory symptoms and emergency room admissions for respiratory illnesses when an algae bloom was present (Kirkpatrick *et al.* 2006).

The pathogenic etiology of most illnesses from direct exposure to ocean water or the marine environment is not

well understood. Fecal coliform levels are typically used as indicators of fecal contamination, but research linking specific pathogens to disease outbreaks is complicated by the broad spectrum of pathogens in beach water (NRC 1999) and the high degree of temporal and spatial variability (Boehm 2007). For these reasons most studies to date have been limited to estimating costs associated with general beach exposure.

METHODS

The first step to determine a cost estimate is to identify the marine-borne pathogens and toxins that are major disease agents rather than those causing a few sporadic cases. Although many pathogens in the marine environment are capable of causing human illness, we focus on those that were likely to have a significant economic impact. Sporadic cases are unlikely to account for significant costs unless the disease is life threatening or requires extensive medical attention. We start by generating a broad list of pathogens that cause human disease (CDC Outbreak Surveillance Summaries 1993–2006; Feldhusen 2000; Lees 2000; Thompson *et al.* 2005). We narrow the list to include only pathogens that have been documented to cause illnesses in the USA due to ocean exposure or seafood ingestion and that are likely to have significant costs because they are widespread or cause severe health consequences.

Estimating the annual human health costs requires an estimate of the incidence of disease and a cost per illness. We review the literature and surveillance and monitoring data to determine an annual incidence of marine-borne disease and health consequences. Using this data, we employ a cost-of-illness model used by the United States Department of Agriculture's (USDA) Economic Research Service (ERS) to estimate economic impacts. The model divides cases into four severity categories and assigns a cost to each (Buzby *et al.* 1996; Frenzen *et al.* 2005). We multiply the total number of cases in each category by the corresponding category cost. The sum over all four categories represents the annual cost for each pathogen.

This approach acknowledges the bimodal nature of many marine-borne diseases, with symptoms that are either mild or severe, and incorporates the level of medical and hospital services used. Cases are categorized by level of

medical care: (1) did not visit a physician or seek medical treatment (lost productivity); (2) visited a physician; (3) were hospitalized; or (4) prematurely died. Given that many marine-borne illnesses are not reported and are relatively mild in severity, assigning a lower cost to illnesses that do not require medical attention is a key aspect to this model.

Other than for *Vibrio* species and *K. brevis*, we find that there are insufficient data to estimate with enough accuracy the pathogen-specific costs of illness due to direct exposure. We therefore adopt a general health cost estimate for direct exposure by extrapolating findings from a beach exposure study in Southern California to the rest of the country.

Disease incidence

Seafood borne

We use information from the CDC's surveillance systems to estimate the number of cases of seafood-borne illness (Table 1), taking into account limitations of surveillance data and underreporting. For each pathogen, we first determine an average annual number of surveillance cases caused by seafood consumption, either from outbreak data (which exclude sporadic cases or cases not identified as part of an outbreak) or from passive surveillance data (which include sporadic cases). For most pathogens, a scaling ratio is applied to estimate the total reported cases that take into account the exclusion of sporadic cases and/or cases not captured by passive or outbreak surveillance. The method for determining the scaling ratio varies by pathogen and depends on the type of surveillance through which that pathogen is reportable.

Pathogens only reportable through outbreak surveillance [*Plesiomonas*, *Staphylococcus*, *Clostridium perfringens*, CFP, NSP (neurotoxic shellfish poisoning) and PSP (paralytic shellfish poisoning)] are scaled by 10, a multiplier proposed by Mead *et al.* (1999) to account for sporadic cases. Some pathogens are reportable through outbreak surveillance as well as passive surveillance (*Vibrio* species, *Clostridium botulinum*, hepatitis A) or active surveillance (*Vibrio* species, *Campylobacter*, *Salmonella* and *Shigella*). For these pathogens, we determine the ratio of outbreak cases to passive cases or to active cases over a five-year period. This ratio is

used to scale up the outbreak estimate. Because the *Vibrio* species is included in both passive and active surveillance, we use this method to scale up the cases from passive surveillance rather than from outbreak data. *Clostridium botulinum* and *Vibrio cholerae* O1 are reportable through passive surveillance and tend to be severe illnesses so we assume most cases are included in the data and do not apply a scaling ratio.

Seafood-borne Norwalk virus cases are subject to very limited surveillance and a high degree of suspected underreporting. We estimate that, of the 27,171 reported outbreak cases of food-borne Norwalk virus from 1998 to 2002, 2% were from seafood (CDC Outbreak Surveillance Summaries 1993–2006; CDC 2006c). We apply this percentage to the 9.2 million cases of food-borne illness from Norwalk virus estimated by Mead *et al.* (1999) and divide by an underreporting ratio of 38 (as reported by Mead *et al.* (1999) for mild illnesses) to get an active surveillance estimate.

Once we adjust the number of outbreak or passive surveillance cases to reflect the total reported seafood-borne cases, we apply an underreporting ratio to calculate a more probable incidence of disease. This ratio accounts for unreported cases due to a failure of medical practitioners to report the illness to public health authorities, limitations in laboratory practices (i.e. failing to perform the necessary diagnostic test, the physician does not obtain a specimen) and/or the ill person's decision not to seek medical help. For seafood-borne illness we assign one of three underreporting ratios to the first two categories (lost productivity and physician visit) depending on illness severity: 38 times the reported number for mild cases, 20 times the reported number for moderately severe cases, and 2 times the reported number for very severe cases (Mead *et al.* 1999). For pathogens with no known underreporting ratio, we apply one of these estimates depending on the type and duration of the disease symptoms. We apply a weighted average underreporting ratio of 67.5 for CFP in this study (based on underreporting in Hawaii and Florida [Hoagland *et al.* 2002]) and an underreporting ratio of 10 is used for PSP and NSP based on an estimate from Todd (1989).

Hospitalizations and deaths are also underreported for several reasons (Mead *et al.* 1999), although to a lesser degree. We apply one underreporting ratio to all pathogens and marine toxins in the two higher severities. Because

Table 1 | Annual incidence estimates for diseases with known etiology from seafood or recreational exposure

	Surveillance cases	Scaling ratio	Total reported	Underreporting ratio*	Incidence estimate
Norwalk virus			4,842 ^o	38	183,996
Hepatitis A virus	5 ^{b,c}	5 ^r	23	3	68
<i>Campylobacter jejuni</i>	7 ^{b,c,d}	250 ^p	1,813	38	68,875
<i>Clostridium botulism</i>	6 ⁿ		6	2	12
<i>Clostridium perfringens</i>	19 ^{c,d}	10 ^o	194	38	7,372
<i>Plesiomonas</i>	2 ^b	10 ^o	20	38	760
<i>Salmonella</i>	52 ^{b,c,d}	14 ^p	732	38	27,824
<i>Shigella</i>	8 ^{b,c,d}	100 ^p	798	20	15,950
<i>Staphylococcus aureus</i>	2 ^{c,d}	10 ^o	17	38	627
<i>V. alginolyticus</i> – seafood	4 ^a	2 ^q	8	20	160
<i>V. alginolyticus</i> – direct	26 ^{a,j,k}				
<i>V. cholerae</i> O1	6 ^a		6	2	12
<i>V. cholerae</i> non-O1	36 ^a	2 ^q	72	20	1,440
<i>V. fluvialis</i>	19 ^a	2 ^q	38	20	760
<i>V. hollisae</i>	7 ^a	2 ^q	14	20	280
<i>V. mimicus</i>	6 ^a	2 ^q	12	20	240
<i>V. parahaemolyticus</i> – seafood	167 ^a	2 ^q	334	20	6,680
<i>V. parahaemolyticus</i> – direct	19 ^{a,j,k}				
<i>V. vulnificus</i> – seafood	57 ^a	2 ^q	114	2	228
<i>V. vulnificus</i> – direct	31 ^{a,j,k,l}				
<i>Alexandrium/Gymnodinium</i> (PSP)	8 ^{b,c,h,i,m}	10 ^o	75	10	750
<i>Gambierdiscus toxicus</i> (CFP)	65 ^{b,c,e,f,g,h,m}	10 ^o	651	67	43,588
<i>Karenia brevis</i> (NSP) – seafood	4 ^{c,i}	10 ^o	44	10	440
<i>Karenia brevis</i> (respiratory) – direct					21,800 ^s

*UR for category 1 and category 2; A UR of 1.3 is used for all pathogens for categories 3 and 4. ^aCDC, COVIS (1999–2006): we included all instances of *Vibrio* isolates in either stool or blood, the primary sites for seafood-borne illness. When there was more than one isolate per patient, we applied the percentage of isolates that were seafood borne to the total number of patients. ^bAhmed (1991). ^cCDC (1993–2006) Outbreak Surveillance Data. ^dHuss et al. (2004). ^eCSPI (2007): we assume an equal number of cases per outbreak for each pathogen and toxin. We applied the percentage of outbreaks attributable to CFP (22%) to the total number of cases. ^fCDC (2006b). ^gCDC (2000). ^hCDC (1996). ⁱHoagland et al. (2002). ^jCDC (2008b). ^kCDC (2006a). ^lShapiro et al. (1998). ^mCDC (2006c). ⁿCDC (2001–2007) National Botulism Surveillance System. ^oMead et al. (1999). ^pRatio of cases in Outbreak Surveillance (CDC 1993–2006) to cases in FoodNet (CDC 2000–2004) from 2000 to 2004. ^qRatio of cases in COVIS (CDC 1999–2006) to cases in FoodNet (CDC 2000–2004) from 2003 to 2004. ^rRatio of cases in Outbreak Surveillance (CDC 1993–2006) to cases in NNDSS (CDC 2001–2005) from 2001 to 2005. ^sHoagland et al. (2009).

there is little published information on the number of seafood-borne illnesses that lead to hospitalization or premature death, our estimate is based on a study of notifiable infectious diseases that found only 79% of AIDS, tuberculosis and sexually transmitted disease cases were reported (Doyle et al. 2002). Given the severity of these illnesses compared with marine-borne diseases, it is likely that the fraction of reported cases in our study is substantially lower. However, in the absence of specific data for the more severe food-borne diseases, we apply an underreporting estimate of 25% to each of these categories across all pathogens.

Direct exposure

The number of illnesses from infection of *Vibrio vulnificus*, *Vibrio parahaemolyticus* and *Vibrio alginolyticus* due to direct exposure is determined from COVIS (CDC 1999–2006) by counting the isolates from wound infections and from the CDC's Surveillance for Waterborne Disease and Outbreaks Associated with Recreation from 2003 to 2006 (CDC 2006a, 2008b). We estimate the total number of respiratory illnesses from aerosolized *K. brevis* exposure by assuming that the annual predicted 218 emergency room

visits (Hoagland *et al.* 2009) accounts for 1% of the total number of cases, a proportion found for other mild illness such as salmonella (ERS 2010). No scaling ratio or underreporting ratio is applied to cases from direct exposure (Table 1), mainly because of a lack of information on the degree of underreporting.

Aside from the three *Vibrio* species and *K. brevis*, there is not enough surveillance data on other pathogens or marine toxins to produce a reliable estimate of illnesses from direct exposure. Therefore, we use a model to estimate the annual number of illnesses from beach exposure in the USA. Specifically, we extrapolate the 1,500,000 excess cases of gastroenteritis found in a study of beach exposure in Southern California (Given *et al.* 2006) to the rest of the country. Using the Environmental Protection Agency's beach and swimming advisory data (EPA 2006) we determine the percentage of beach days (number of beaches multiplied by the number of swimming days in a year) for each state that had at least one notifiable action (either a closure or a swimming advisory) due to high levels of indicator bacteria. We multiply this by the total number of swimming participation days from national marine-recreation participation data (Leeworthy & Wiley 2001) to estimate exposure at the state level. Using the proportion of excess cases of gastrointestinal illness to our exposure estimate (in days) in California we estimate excess gastrointestinal cases in every other state.

Estimating cost

Once an incidence estimate is determined, we assign a cost to each of the four severity categories. We use the proportion of illnesses that fall into each category to determine a total cost for each pathogen and marine toxin, and exposure to contaminated beach water.

Proportions

To estimate the proportion of cases that falls into each category, we used several data sources and follow the method for categorization that was used by ERS (Table 2). Each case is included in only one of the four categories. If the reported hospitalizations include cases that also died, we exclude 90% of the deaths from the hospitalized proportion because

it has been estimated that 90% of patients who died were hospitalized first (Frenzen *et al.* 1999). Except for the marine toxins, the proportion of cases requiring no medical care is determined by subtracting the sum of the last three categories' proportions from one. To determine the number of cases in each category from aerosolized *K. brevis*, we assign the estimated number of emergency room visits (Hoagland *et al.* 2009) to the physician visit category and, using proportions similar to those of a low severity illness, extrapolate to estimate the total cases in the other three categories.

For the majority of the pathogens, the proportion of cases in the physician visit category was unavailable. For these pathogens, we assume that for mild illnesses the proportions are similar to those published by ERS for *Salmonella*, and for more severe illnesses the rates published for *E. coli*. An illness was deemed either mild or severe based on the types and duration of symptoms. The proportions for PSP, NSP and CFP are based on studies that reported approximately 30% of CFP cases have only gastrointestinal symptoms and 70% have neurological symptoms (Lawrence *et al.* 1980; de Fouw *et al.* 2001; Lubber *et al.* 2007, unpublished), although these proportions vary by geographic location and specific outbreak. We assume that some medical help would be sought for neurological symptoms. The proportions used for illnesses from contaminated beach water are based on the typically mild symptoms experienced.

Cost

While some cost estimates include intangible factors such as impaired quality of life or non-medical health costs (Todd 1995; Scott *et al.* 2000; Scharff *et al.* 2009), we estimate a cost for each category that only includes lost wages, physician and hospital services, and the statistical cost of a premature death. The cost estimates do not include chronic effects, pain and suffering, inconvenience, and time lost from recreational activities. In a broader study of food-borne illness, *Salmonella* cases not requiring a physician's visit were found to cost (in 2008 dollars) US\$52 while cases requiring a physician's visit cost US\$536 (Frenzen *et al.* 1999; ERS 2010). Mild cases of *E. coli* infection had similar costs, with US\$30 per case with no physician visit and US\$540 per case for those with a physician visit. Each case of *Salmonella* that required hospitalization cost over

Table 2 | Severity category proportion of illnesses and corresponding cost estimates by causative agent

	Proportions				Cost per year (in US\$ millions)				Total
	1	2	3	4	1	2	3	4	
Norwalk virus	0.898 ^a	0.100 ^b	0.0023 ^c	0.00001 ^c	8.26	9.20	0.14	0.84	17.69
Hepatitis A virus	0.791 ^a	0.186 ^d	0.0216 ^c	0.00096 ^c	0.0027	0.0063	0.0064	0.14	0.16
<i>Campylobacter jejuni</i>	0.941 ^a	0.054 ^f	0.0051 ^c	0.00008 ^c	3.24	1.86	0.13	0.59	5.82
<i>Clostridium botulism</i>	0.0 ^h	0.138 ^g	0.7931 ^c	0.06900 ^c	0	0.00083	0.062	2.69	2.75
<i>Clostridium perfringens</i>	0.887 ^a	0.113 ^e	0.0002 ^c	0.00003 ^c	0.330	0.42	0.00042	0.035	0.78
<i>Plesiomonas</i>	0.887 ^a	0.113 ^e	0.0 ^k	0.0 ^k	0.034	0.043	0	0	0.077
<i>Salmonella</i>	0.875 ^a	0.113 ^e	0.0120 ^c	0.0004 ^c	1.220	1.57	0.12	1.90	4.81
<i>Shigella</i>	0.800 ^a	0.186 ^d	0.0139 ^c	0.00002 ^c	0.640	1.48	0.15	0.083	2.35
<i>Staphylococcus aureus</i>	0.886 ^a	0.113 ^e	0.0010 ^c	0.00001 ^c	0.028	0.035	0.00022	0.0012	0.065
<i>V. alginolyticus</i>	0.604 ^a	0.186 ^d	0.2000 ^c	0.01020 ^c	0.0048	0.015	0.021	0.53	0.57
<i>V. cholerae</i> O1	0.334 ^a	0.186 ^d	0.4568 ⁱ	0.02273 ⁱ	0.00020	0.0011	0.036	0.89	0.92
<i>V. cholerae</i> non-O1	0.503 ^a	0.113 ^e	0.3363 ⁱ	0.04737 ⁱ	0.036	0.081	0.32	22.17	22.6
<i>V. fluvialis</i>	0.403 ^a	0.186 ^d	0.3867 ⁱ	0.02463 ⁱ	0.0150	0.071	0.19	6.08	6.36
<i>V. hollisae</i>	0.217 ^a	0.186 ^d	0.5968 ⁱ	0.00000 ⁱ	0.0030	0.026	0.11	0	0.14
<i>V. mimicus</i>	0.466 ^a	0.186 ^d	0.3030 ⁱ	0.04478 ⁱ	0.0056	0.022	0.047	3.50	3.57
<i>V. parahaemolyticus</i>	0.694 ^a	0.113 ^e	0.1837 ⁱ	0.00886 ⁱ	0.23	0.38	0.80	19.22	20.63
<i>V. vulnificus</i>	0.0 ^h	0.118 ^g	0.5687 ⁱ	0.31333 ^{j,i}	0	0.013	0.84	232.18	233.04
PSP	0.300 ^q	0.3375 ^p	0.3375 ^s	0.02500 ^{n,o,p}	0.011	0.13	0.33	12.12	12.58
CFP	0.300 ^q	0.4490 ^p	0.2500 ^{t,u,v,w,x}	0.00100 ^{n,o,p,r}	0.65	9.79	2.11	4.23	16.78
<i>K. brevis</i> (NSP)	0.300 ^q	0.3400 ^p	0.3600 ^s	0.0 ^k	0.0067	.075	.206	0	0.29
Seafood subtotal					14.17	25.21	5.60	306.44	351.96
<i>V. alginolyticus</i>	0.850 ^a	0.0	0.1369 ^{l,m}	0.00971 ^{l,m}	0.0012	0	0.035	1.24	1.27
<i>V. parahaemolyticus</i>	0.600 ^a	0.0	0.3896 ^{l,m}	0.01493 ^{l,m}	0.00057	0	0.074	1.42	1.49
<i>V. vulnificus</i>	0.170 ^a	0.0	0.65 ^{l,m}	0.1842 ^{l,m}	0.00025	0	0.20	28.09	28.29
<i>K. brevis</i> (respiratory)	0.899 ^z	0.10 ^y	0.001 ^y	0.0 ^y	0.98	1.1	0.22	0	2.29
Contaminated beach water	0.9899 ^a	0.01 ^z	0.0001 ^z	0.0 ^z	255.4	25.8	5.16	0	286.36
Direct exposure subtotal					256.38	26.90	5.69	30.75	319.70
Grand total					271.07	52.12	11.32	337.53	672.02

^a1-sum of proportions for categories 2–4. ^bWiddowson et al. (2005). ^cMead et al. (1999). ^dERS, Online Cost Calculator for Estimating the Economic Cost of Illness (*E. coli*). ^eERS, Online Cost Calculator for Estimating the Economic Cost of Illness (salmonella). ^fBuzby et al. (1996). ^g1-sum of proportions for categories 1–4. ^hGiven the severity of the illness and the high proportion of hospitalized cases we make the assumption that all cases seek some level of medical care. ⁱCDC, COVIS (1999–2006). ^jShapiro et al. (1998). ^kNo record of death or hospitalization in the USA (CDC). ^lCDC (2008b). ^mCDC (2006a). ⁿCDC (2006c). ^oCDC (2000). ^p7 (Lawrence et al. 1980) sum of proportions for categories 3 and 4. ^qLuber et al. (2007, unpublished). ^rHoagland et al. (2002). ^sTodd (1995). ^tFDH (2006). ^uCDC (2006b). ^vCDC (1998). ^wCDC (1993). ^xCDC (1982). ^yOur estimates, assumed similar to low severity/salmonella. ^zOur estimates, based on typically minor symptoms.

US\$11,000; each *E. coli* case with hospitalization cost about US\$7,400. Based on these findings, we assume in our calculations that an illness that does not require a physician visit costs US\$50, a physician visit costs US\$500, and each hospitalization costs US\$10,000. We use the same category costs for illness from exposure to contaminated waters.

Although rare, premature deaths due to *Salmonella* and *E. coli* were estimated to cost roughly US\$5 million (ERS 2010). This estimate is based on two widely cited labor market studies (Fisher et al. 1989; Viscusi 1995) that use the hedonic-wage approach or ‘willingness to pay’. An alternative is the ‘human capital’ approach developed by

Landefeld & Seskin (1982), which takes into account the age of disease onset, but we lack sufficient data to quantify the cost of premature death by this method. Estimates of the value of a statistical life (VSL) range considerably depending on the approach used but several studies have suggested a reasonable estimate is about US\$5 million with a range of uncertainty of about US\$3.2 million (Fisher *et al.* 1989; Viscusi 1992, 1993; EPA 1997; Desvousges *et al.* 1998).

Sensitivity analysis

Our model includes several parameters that are difficult to measure accurately. In several instances, we had to make assumptions to estimate these parameters in our model and, as a result, our cost estimates are characterized by varying degrees of uncertainty. To quantify this uncertainty we conduct a sensitivity analysis for seafood-borne illness costs and pathogen-specific illness from direct exposure. While there is also uncertainty in the model estimates for illness from beach contamination and from unknown etiology, there were too few parameters to conduct a detailed sensitivity analysis. The estimates of illness from beach contamination and from unknown etiology should be considered order of magnitude estimates.

For seafood-borne and pathogen-specific illness estimates, we perturb the scaling ratio, the underreporting ratio and the proportion by 20% (two pathogens have scaling ratios of one, so they are not varied since a scaling ratio cannot be less than one). Because it is necessary to maintain the unit sum across the severity category proportions, we modified the proportions in the adjacent categories when perturbing these proportions based on the rationale that uncertainty in a proportion would likely be reflected in the adjacent category. For example, while it is possible that 20% of the people who did not seek medical care (category 1) did in fact see a doctor (category 2), it is less likely that a person who was incorrectly determined to have not sought medical care (category 1) in fact died (category 4).

RESULTS AND DISCUSSION

We calculate the annual health costs of seafood-borne diseases to be US\$350 million and the costs of illnesses from

direct exposure to *V. vulnificus*, *V. parahaemolyticus*, *V. alginolyticus* and aerosolized *K. brevis* to be over US\$30 million. We estimate the cost of the 5 million cases of gastrointestinal illness from beach exposure to be almost US\$300 million. Combined, this suggests that marine-borne diseases with known etiology in the USA have annual health costs on the order of US\$600 million (Figure 1).

Our estimate of pathogen-specific, seafood-borne illness cost excludes cases with unknown pathogenic etiology, including those that were misdiagnosed or could not be identified as marine borne and therefore is likely an underestimate of the total cost of seafood-borne disease. Over 80% of the estimated 76 million annual cases of food-borne disease in the USA have an unknown etiology (Mead *et al.* 1999). Assuming that 5% of the 62 million cases with unknown etiology are from seafood (Huss *et al.* 2004; CSPI 2007), the number of additional seafood-borne cases could be over 3 million with costs of almost \$300 million (we assume here that these cases have severity proportions similar to those of Norwalk virus). Including the cost of seafood-borne illnesses with unknown etiology almost doubles the total cost of seafood-borne illness.

Cost of seafood-borne illness

Our results indicate that premature deaths contribute most to the total costs of seafood-borne illness (US\$306 million) (Table 2), with the remainder due to medical care (US\$25 million for physician visits and US\$6 million for hospitalizations) and lost productivity (US\$15 million). *Vibrio vulnificus* is the most costly marine-borne pathogen, accounting for about a third of the total seafood-borne costs and over 85% of the costs of *Vibrio* infections from direct exposure (Figure 1). This is primarily a result of the high rate of premature death among *V. vulnificus* cases. With a death rate of 31% for seafood-borne infection and 18% for infections from direct exposure, the cost from premature death (US\$238 million) accounts for 99% of the total *V. vulnificus* health costs and 75% of the total cost of premature death.

Following *V. vulnificus*, the five most costly pathogens result in health costs between US\$15 and US\$20 million annually. *Vibrio parahaemolyticus* and *V. cholerae* non-O1 have an annual cost on the order of US\$20 million, while

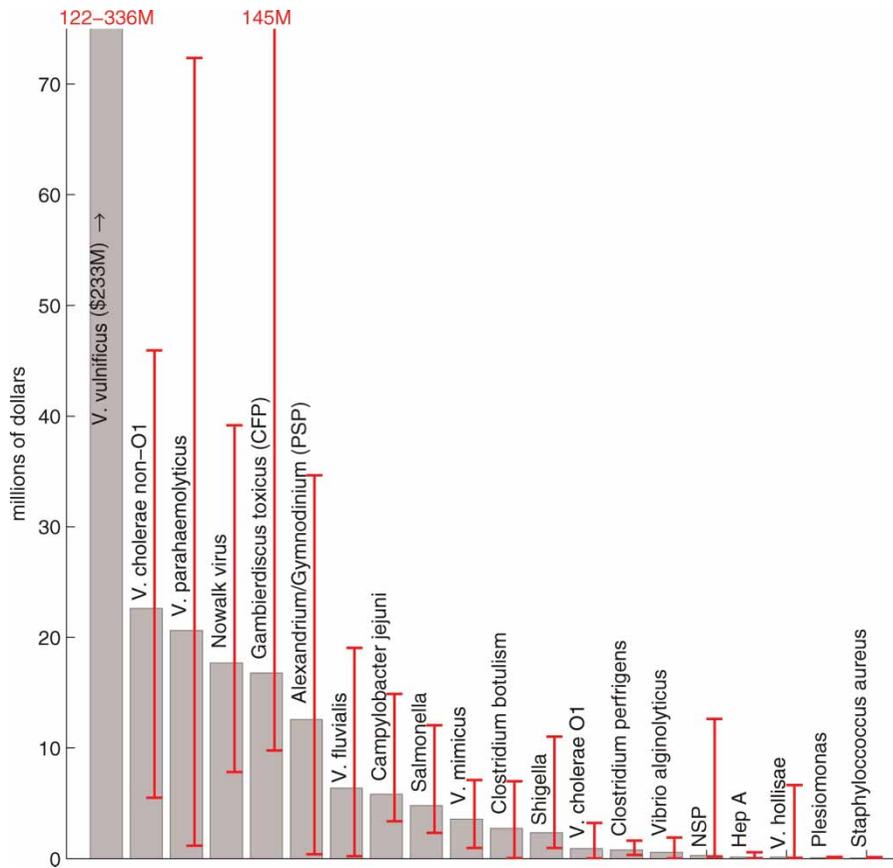


Figure 1 | Overall cost of pathogen-specific, marine-borne illnesses.

Norwalk virus and CFP rank next with costs of US\$18 and US\$17 million, respectively. PSP costs are slightly lower, around US\$15 million. *Campylobacter* and *Vibrio fluvialis* have costs between US\$5 million and US\$10 million while *Vibrio mimicus*, *Shigella*, *Clostridium botulism* and *Vibrio cholerae* all have costs between about US\$1 million and US\$4 million. The rest of the pathogens have individual annual costs less than US\$500,000.

Cost of illness from direct or recreational exposure

The health costs from direct exposure are more difficult to assess, but results from the limited surveillance data and the extrapolation analyses suggest that they are on the order of US\$300 million/year (Table 2). Using incidence data from COVIS, it is estimated that *V. vulnificus* infections cost over US\$28 million while *V. alginolyticus* cost over US\$1 million. *Vibrio parahaemolyticus* infections are less

common from direct exposure and have costs of about US\$1.5 million compared with the US\$21 million from ingestion of seafood. Respiratory illness from *K. brevis* corresponds to a cost of over US\$2 million. The health costs from contaminated beach water are the largest component of direct exposure health costs. We estimate a total of over 5 million cases of excess gastrointestinal illness due to beach exposure, corresponding to almost US\$300 million/year.

Sensitivity analysis

To evaluate cost model sensitivity, we perturbed the model variables by 20% in various combinations to yield 243 different cost estimates for all of the seafood-borne pathogens except Norwalk virus, which had only 81 cost combinations because no scaling ratio was used. Pathogens causing illness from direct contact had only nine cost combinations because no scaling ratio or underreporting ratio was used.

In the sensitivity analysis, the total cost for pathogen-specific illness ranged from US\$166 million to US\$967 million. However, random sampling of the sensitivity results indicates that when the lower and upper 5% of the possible combinations are excluded, the total cost range is approximately US\$300 million to US\$550 million, considerably closer to the point estimate.

Figure 1 includes error bars showing the 2.5 and 97.5 percentiles of the costs for each pathogen in the sensitivity analysis. The pathogens with the greatest cost range are *V. vulnificus*, *V. parahaemolyticus* and CFP, while *Plesiomonas*, *Staphylococcus* and hepatitis A have the narrowest ranges. Pathogens with a high uncertainty relative to their estimated cost, such as CFP and *Vibrio hollisae*, tend to have high hospitalization rates (category 3) and low death rates (category 4). The sensitivity analysis perturbed adjacent categories by 20% to maintain the same total number of cases. For pathogens with high hospitalization rates, these perturbations transferred cases to the death category, resulting in a broader range of cost outcomes owing to the high cost of death.

We examined the impact of death on the cost uncertainty because it accounts for a large fraction of the total cost. To assess whether the high cost of death or a high death rate among a few pathogens was driving the total cost uncertainty, we also ran the sensitivity analysis both with an altered cost of a premature death and by removing the cost of death from the estimate. Although the cost range without death decreased under the different scenarios, the upper and lower bounds of the cost estimates remained proportionally similar to the point cost estimate, suggesting that death alone does not primarily drive the range of uncertainty.

One goal of this study was to identify the pathogens and marine toxins that prevention and monitoring efforts should target to produce the most significant economic benefits. *Vibrio vulnificus* is the most costly pathogen in our study with an annual cost of illness ten times higher than any other pathogen; it makes up 66% of the seafood-borne illness health costs and 26% of the total health costs. The high costs are primarily driven by high death rates, underscoring the public health importance of this illness. Despite efforts by government agencies to address the problem, deaths due to *V. vulnificus* have not declined over recent years (CDC 1999–2006; FDA 2009).

While *V. vulnificus* is the most significant contributor to the total health cost estimate, other naturally occurring pathogens also have relatively high health costs. For example, *V. parahaemolyticus* had an annual health cost of over US\$20 million, and recent evidence suggests that illness from this pathogen may be increasing. In 2006 a total of 177 cases were reported in New York, Washington and Oregon, substantially more than in the previous five years (CDC 2006d). CFP had health costs approaching US\$17 million. As a consequence of changing environmental conditions, such as warming ocean temperatures and coral bleaching, we may see an increase in the source of the toxin *Gambierdiscus toxicus* in the future. Milder, self-limiting illnesses from both seafood consumption and direct or recreational exposure also have a significant economic impact. Although Norwalk virus rarely results in death, the costs of the estimated 184,000 cases annually approach US\$18 million. Similarly, the total cost of gastrointestinal illness from beach exposure is significant because of the large number of cases (estimated 5 million), even though most do not seek medical care.

The cost estimates for seafood-borne illness and from beach contamination require assumptions for the model parameters. Most of the parameters based on published data and our assumptions are conservative, but uncertainty remains in our estimate. For example, the estimated cost of a premature death is an important factor in the results. Without the cost of death included, the total health cost from illness with known etiology is US\$335 million – about 50% of the overall cost. The cost of premature death accounts for almost 90% of the total seafood-borne health costs. The cost model assumes that the VSL is US\$5 million. Although VSL in the literature can range from US\$0.5 million to US\$21 million (Viscusi & Aldy 2003), the commonly used range is substantially narrower, from about US\$5.5 million to US\$7.5 million (Kniesner et al. 2007). Among federal agencies, the FDA estimates a VSL to be about US\$8 million, the EPA has a slightly lower estimate of US\$7 million, and the ERS/USDA estimate is about US\$5.5 million. We have used the lower end of this range, and increases in the VSL would substantially increase the total health cost estimates.

In addition to the conservative parameter estimates, the cost estimate for marine-borne illness may represent a lower bound of the true costs because we do not include costs that

are difficult to measure such as chronic effects and pain and suffering. A recent study that used a cost-of-illness model developed by the FDA that included a measure of chronic pain and suffering and functional disability found the total cost of food-borne illness to be US\$152 billion (Scharff *et al.* 2009; Scharff 2010). The productivity losses associated with pain and suffering are also likely to be important, but assignment of reliable cost estimates introduces additional uncertainty. We used a lost productivity estimate that only included lost days of work and forgone compensation, so our cost per case is about US\$1,300 versus a cost of about US\$1,800 per case in the alternative cost model (Scharff 2010).

Similarly, chronic health effects from marine-borne illnesses may introduce substantially higher costs than we have assumed. While there are few data from which to quantify the prevalence of long-term symptoms, it has been estimated that chronic sequelae may occur in 2–3% of food-borne illnesses generally, and that the costs of these health consequences could be greater than the costs of the acute symptoms (Lindsay 1997). For example, the estimated cost of chronic effects from ten cases of *E. coli* in 2006 was US\$7,363,814 (2007 dollars) in medical care expenses alone (ERS 2010). The cost estimate here does not address marine agents that are thought to be particularly associated with chronic effects, such as heavy metals or persistent organic pollutants. Similarly, we do not incorporate low cost but high frequency costs often associated with mild illness such as over-the-counter medication.

The health cost estimates depend in part on disease incidence. Exposure and incidence rates reflect patterns of human behavior around the oceans and seafood. For example, there are differences in incidence rates among certain subgroups, such as those with compromised immune systems or island/coastal populations who are high seafood consumers. It has been shown that Asian and Pacific Island communities in California and tribal communities in the Pacific Northwest have an increased risk of seafood-borne disease because of their greater seafood consumption (NEJACM 2002), and immunocompromised individuals have the greatest risk of death from exposure to *V. vulnificus* (CDC 2010). Future research should include an evaluation of the costs for specific communities.

Disease incidence can be affected by monitoring and warning systems that are in place. For example, shellfish

are routinely monitored for HAB (harmful algal bloom) toxins, and harvesting is restricted when toxins are detected. This monitoring is widely credited with limiting illness from HAB toxins in shellfish. To reduce risks from direct exposure to aerosolized brevetoxins, a real-time reporting system was recently implemented on several public beaches in Florida (Kirkpatrick *et al.* 2008). A useful extension of the results reported here would be an evaluation of the costs of monitoring and warning programs relative to the residual health costs to determine where additional investments in monitoring may be warranted.

In the absence of a model designed specifically to estimate the cost of seafood-borne illness, we use a model that was developed to estimate the cost of food-borne illness in general. There may be differences, however, between the average American and the average seafood consumer. The average American consumes less seafood than other meat and poultry. In 2004, Americans consumed four times more beef than seafood and more than five times the amount of poultry (NOAA 2004; Davis & Lin 2005). Seafood consumers also tend to be more educated (He *et al.* 2003) and have a higher household income (Hicks *et al.* 2008) – two factors that may be associated with a greater loss of productivity. Similar distinctions may be important for direct exposure risks at beaches, as recreational beach participation rates increase with both education level and income (Leeworthy *et al.* 2005). Despite these possible limitations this model allows us to estimate the health costs of seafood-borne illness that can be used as a foundation for future research to establish a more precise estimate.

CONCLUSIONS

We estimate the acute health cost of marine-borne disease in the USA to be close to a billion dollars annually, with seafood-borne disease making up two-thirds of the cost, and illness from direct exposure to the marine environment accounting for the rest. We identify several pathogens that contribute substantially to these costs, notably the *Vibrio* species, CFP and Norwalk virus. Incomplete reporting of marine-borne illnesses, unknown pathogenic etiology of many food-borne cases, and limitations in identifying specific pathogens in beach recreation cases introduce considerable

uncertainty into the overall estimate. Future research should focus on resolving these uncertainties, on extending the estimate to include the cost of chronic health effects and pain and suffering, and determining an economically optimal policy response to preventing marine-borne illness.

Relative to the health costs of other illnesses, such as cancer, HIV/AIDS and diabetes, the cost of marine-borne illness is small. Annual direct medical costs are estimated to be US\$74 billion for cancer (Meropol & Schulman 2007), over US\$32 billion for AIDS/HIV (Schackman et al. 2006; CDC 2008a) and about US\$116 billion for diabetes (ADA 2008). The costs of marine-borne disease are low in part because public health and coastal and marine resources departments in the USA have been effective at limiting the threats to human health. In developing countries, where public health infrastructure is often less robust, disease associated with marine environments is suspected to have a greater prevalence (Todd 2006).

One goal of estimating the cost of marine-borne illness is to determine the economically optimal policy response to managing marine health. If the cost of preventing marine-borne illness is significantly outside the range of cost uncertainty, then from a policy point of view, a more precise estimate may not be necessary. Future research should focus on determining the appropriate policy for preventing marine-borne illness based on the optimal economic response and compare it with other public health problems.

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