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Short Contributions

Quantitative Risk Assessment of the Pathways by Which West Nile Virus Could Reach Hawaii

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Abstract: The introduction of West Nile virus (WNV) to Hawaii could have severe impacts on human health, wildlife health and, as a result, Hawaii's tourism-based economy. To provide guidance for management agencies seeking to prevent the introduction of WNV, we performed a quantitative assessment of the pathways by which WNV could reach Hawaii from North America. We estimated the rate of infectious individuals reaching Hawaii by the following means (1) humans on aircraft, (2) wind-transported mosquitoes, (3) human-transported mosquitoes, (4) human-transported birds or other vertebrates, and (5) migratory birds. We found that pathways 3 and 4 represented the highest risk. We estimated that each year, 7–70 WNV infectious mosquitoes will reach Hawaii by airplane when WNV becomes well established in the Western U.S. Exemptions in current quarantine regulations will also result in the import of birds that will be infectious with WNV for 0.3–2.2 bird-days each year. We propose actions that would substantially reduce the risk of WNV reaching Hawaii by these means, including reinstating aircraft disinsection in cargo holds and altering bird quarantine rules. Finally, research is urgently needed to determine whether a migratory bird can survive the migration from North America to Hawaii with a viremic WNV infection.

Key words: arbovirus, introduction, mosquito, quarantine, disease

Introduction

Since its first appearance in North America in 1999, West Nile virus (WNV) has spread across the continent and into Central America, infecting more than 14,000 people and causing over 500 deaths (Centers for Disease Control and Prevention [CDC], 2003). In addition, it has killed hundreds of thousands of birds, in some cases leading to local reductions in populations of greater than 90% (Hochachka et al., 2004). Clearly, WNV is capable of causing significant impacts on bird populations, and substantially impacting human health.

Hawaii has 48 endemic species or subspecies of birds of which 30 are listed as endangered by the U.S. Fish and Wildlife Service (Jacobi and Atkinson, 1995). Many of these species are extremely susceptible to vector-borne avian diseases which were absent during the evolution of Hawaii's avifauna (Van Riper et al., 1986). For these reasons, the introduction of WNV could have devastating effects on

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populations of native Hawaiian birds and lead to the extinction of many species.

The impacts of WNV on Hawaii's native avifauna and human health could significantly affect the tourism industry which is the backbone of Hawaii's economy. In response to the combined human, wildlife, and economic health threats of WNV to Hawaii, an interinstitutional, interagency "West Nile virus working group" has been established to provide guidance for management agencies seeking to prevent the introduction of WNV. To facilitate this work, we performed a quantitative assessment of the pathways by which WNV could reach Hawaii and suggested actions that could reduce the risks of these pathways.

Methods

We estimated the rate of infectious mosquitoes or vertebrate hosts reaching Hawaii each year by natural or human-assisted means during the peak WNV season (≈120 days long in New York State; Bernard et al., 2001). For WNV to become established in Hawaii, an infectious mosquito would need to arrive in Hawaii, find and successfully transmit WNV to a suitable host, or an infectious host would need to be bitten and transmit WNV to a suitable vector. Hawaii has several competent mosquito vectors (*Culex quinquefasciatus, Aedes albopictus, Ae. Vexans, Ae. Aegypti*; Sardelis et al., 2001) and many suitable avian hosts (e.g., House sparrows, *Passer domesticus*, House finches, *Carpodacus mexicanus*; Komar et al., 2003) that make the establishment of WNV possible or even likely if an infectious mosquito or host were to reach Hawaii.

We estimated the number of mosquitoes reaching Hawaii on each arriving plane from an average of two studies. The first, based on 928 planes landing in Japan over the period 1975–1981, found an average of 0.9 live mosquitoes per airplane (Takahashi, 1984). Another based on 307 planes landing in Australia during the period 1974–1979 found an average of 2.2 live mosquitoes per airplane (Russell et al., 1984). Greater than 95% of the mosquitoes on airplanes in both studies were *Culex pipiens* or *Culex quinquefasciatus*. We estimated the number of mosquitoes arriving in Hawaii in each shipping container from a study of 11,000 containers by the New Zealand Ministry of Agriculture and Forestry (MAF, 2003) that did not specify whether the mosquitoes found were adult or larvae.

The rate of mosquitoes reaching Hawaii by wind was estimated as less than one per 4 million years based on the fact that mosquitoes were unable to successfully colonize Hawaii (Hardy, 1960) in at least 4 million years that islands in the Hawaiian chain would have had suitable habitat. This may be a slight underestimate, because the number of mosquitoes required to establish a population in Hawaii is most likely greater than the number required to initiate a WNV cycle.

We estimated the fraction of mosquitoes that would be infectious as the fraction of infected *Culex quinquefasciatus* mosquitoes that are able to transmit the virus with a bite, 0.22 (Sardelis et al., 2001), multiplied by the average minimum infection rate (MIR; an estimate of prevalence) of the endemic mosquito vectors during the months July–October. We used a range of MIRS based on data from New York in 2000 (MIR=2 or 0.2% of *Culex pipiens* mosquitoes tested; Bernard et al., 2001), and Colorado in 2003 (MIR=20, or 2% of *Cx. tarsalis* mosquitoes tested; Pape, 2004).

We estimated the number of vertebrate hosts arriving in Hawaii each year from the health certificates of imported birds (Gluzberg, 2004) and import records for Hawaii (Hawaii Department of Agriculture [HDA], 2002). Most species of birds are required to be placed in a mosquito-proof quarantine facility for 7 days prior to transport to Hawaii (Department of Agriculture [DOA], 2003). Previous research (Komar et al., 2003) suggests that 7 days is long enough for most species of birds to clear WNV from their bloodstream (but not other organs, see Komar et al., 2003) preventing transmission to biting mosquitoes. However, six species are currently exempt from this quarantine and are possible carriers of WNV to Hawaii: Chickens (*Gallus domesticus*), Pheasants (*Phasianus colchicus*), Quail (*Coturnix japonicus*), Chukars (*Alectoris chukar*), Rock doves (*Columbia livia*), and Budgerigars (*Melopsittacus undulatus*) (DOA, 2003). We estimated the fraction of these animals that would be infectious using the following expression:

$$\frac{\varphi}{365}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(\int_{4}^{7.3} I_m(v)N(v_i,\sigma)dv + \int_{7.3}^{\infty} N(v_i,\sigma)dv\right)$$

where φ is the fraction of birds exposed to WNV (0.326, taken from a sero-survey in NY following the 1999 outbreak (Komar et al., 2001) and assuming transported birds are held outdoors), 365 is the number of days in a year, which assumes the transport of each animal is equally likely on any given day, the summation is over the viremic period n (in days) for that species (Komar et al.,

Table 1. Estimated Number of Infectious Mosquitoes or Hosts Reaching Hawaii Each Year[m]

Pathway	No. arriving in Hawaii from North America per year	Fraction infectious	Rate of infectious individuals arriving in Hawaii per year
1. Human	3,900,000[a]	~0[b]	~0
2. Wind-blown mosquito	$<1 \times 10^{-6}$	0.00044–0.0044[c]	$< 1 \times 10^{-7}$
3. Human-transported mosquito	Air: 85 flights/day,[d] × 120 days/year × 1.55 mosquitoes/flight	0.00044–0.0044[c]	7.0–70.0
	Sea: 418,332 containers[e], × 0.0005 live mosquitoes/container, × 120 days/year	Adults: 0.00044–0.0044[c] Larvae[f]: 9.2×10^{-7}– 9.2×10^{-6}	Adults: 0.06–0.6 Larvae: 0.0001–0.001
4. Human transported vertebrate	Birds[g]:	Birds[g]:	Birds[g]:
	CHICK: 66–10,069	7.7×10^{-5}	0.003–0.5[h]
	RODO: 25–830	9.6×10^{-4}	0.02–0.8[h]
	BUDG: 2252–9207	9.5×10^{-5}	0.2–0.9[h]
	RNPH: 0–1160	8.4×10^{-6}	0–0.01[g]
	JAQU: 92–167	1.2×10^{-4}	0.01–0.02[g]
	Frogs: 25[i]	Frogs: ? (see Discussion)	Frogs: ? (see Discussion)
5. Migratory bird		(see Discussion)	(see Discussion)
	Shorebirds: 25,000[j]	Shorebirds < 0.018[k]	Shorebirds < 452[g]
	Ducks: 800[j]	Ducks < 0.019[l]	Ducks < 14.8[g]

[a]For 2000, Hawaii Department of Business, Economic Development and Tourism (DBEDT-HI, 2001).
[b]The peak viremia for immunocompetent humans (130 or $10^{2.1}$ plaque-forming units [PFU]/ml) (Biggerstaff and Petersen, 2002) is too low to infect the mosquito species present in Hawaii.
[c]For *Culex quinquefasciatus*.
[d]For 2003, DBEDT-HI (2001).
[e]For 2002 [Iris Ishida, Hawaii Department of Transportation, Harbors Division, personal communication February 4, 2004].
[f]One of 1400 offspring of infected *Culex pipiens* was infected (Dohm et al., 2002).
[g]Four-letter species abbreviations and variance (n = number of birds, × number of days used to estimate variance after removing species-level differences in the mean): CHICK, Chicken, $\sigma^2 = 0.62$, $n = 84$; Langevin et al. (2001); RODO, Rock dove, $\sigma^2 = 1.22$ (Columbiformes, $n = 33$); BUDG, Budgerigar, $\sigma^2 = 0.78$ (Psitaciformes, $n = 21$); RNPH, Ring-necked pheasant, $\sigma^2 = 0.42$ (Galliformes, $n = 36$), JAQU, Japanese quail, $\sigma^2 = 0.42$ (Galliformes, $n = 36$).
[h]Numbers represent infectious bird-days for each species.
[i]Species unknown, Hawaii Department of Agriculture (HDA, 2002).
[j]Shorebirds are Pacific golden plover (80%), Ruddy turnstone (15%), Wandering tattler (4%), Sanderling (1%), ducks are Northern shoveler (60%), Northern pintail (25%), Lesser scaup (8%), Canvasback (2%), American widgeon (5%) [U.S. Fish and Wildlife Service, unpublished data]—see Gluzberg (2004).
[k]Shorebird mean daily viremias based on killdeer, $\sigma^2 = 1.90$ (Charadriiformes, $n = 18$).
[l]Duck mean daily viremias based on Mallard, $\sigma^2 = 1.75$ (Anseriformes, $n = 25$).
[m]See Methods for details of parameter estimation.

2003). This expression calculates the number of infectious bird-days that each imported individual bird represents. The terms in parentheses represent the integral of the probability distribution of an animal's viremia on day i assuming a normal distribution after log-transformation with mean $\log_{10}$ (viremia), v_i, (Komar et al., 2003) and variance, σ^2 (calculated using unpublished data from Komar et al., 2003; see Table 1) multiplied by the probability of a bite leading to a disseminated infection in a mosquito, I_m, given the host's viremia, v. This probability, I_m, was based on a vector competency study of *Aedes albopictus* (Sardelis et al., 2002):

$$I_m = 0.30 * \log_{10}(v) - 1.19; (I_m = 0 \text{ for } \log_{10}(v).<4.0, \text{ and } I_m = 1 \text{ for } \log_{10}(v)<7.3)$$

We used this relationship rather than one for the more ornithophillic (bird-biting) *Culex quinquefasciatus* because *Ae. albopictus* is more sensitive to infection at lower host viremia (Sardelis et al., 2001).

Results

The rate of infectious mosquitoes reaching Hawaii by plane was higher than that by boat which was orders of magnitude higher than that by wind (Table 1). The rate of infectious hosts reaching Hawaii was highest for Budgerigars, lower for Rock doves and adult Chickens, and lowest for other birds and humans (Table 1). We could not accurately estimate the rate of infectious migratory birds reaching Hawaii (see below). However, the risk from mosquitoes is likely to be higher than the risk from birds or other hosts, because mosquitoes are infected with WNV for life (*Culex quinquefasciatus* lifespan 30–64 days; Oda et al., 2002), whereas most birds are infectious to mosquitoes for less than 7 days (Komar et al., 2003).

Discussion

Our analyses show that the greatest known threat of West Nile virus introduction to Hawaii from North America is through mosquitoes transported by airplanes (Table 1). The most effective action to reduce this threat would be to reinstate aircraft disinsection (killing insects with chemicals) using a residual insecticide, especially in cargo holds where research suggests 82% of live mosquitoes are carried (Takahashi, l984). Since most planes flying to Hawaii come from California, where WNV has not yet completely established, the risk from this pathway is expected to increase in the next few years.

The next highest threat is from imported birds that are exempt from quarantine. Removing this exemption for all birds except adult chickens would substantially reduce this threat and have minimal effects on Hawaii's economy. It should also be noted that the current quarantine description does not state that birds must be held individually, and direct transmission of WNV between cage-mates during the quarantine (Komar et al., 2003) could lead to the introduction of WNV from quarantined birds; we propose that this be amended immediately. Additionally, pending further research on amphibians and reptiles' exposure and host reservoir competency, they should also be quarantined prior to shipment to Hawaii, because research has shown that some amphibians are competent WNV hosts (Kostyukov et al., 1986).

Our calculations for vertebrate hosts assume that animals were equally likely to be shipped each day of the year. If animals are shipped during the peak WNV transmission period, the risk will be higher than calculated. Requiring that shipping of animals to Hawaii be done during non-WNV-peak months would substantially reduce this risk pathway.

One important unanswered question is the fraction of migratory birds that would be infectious with WNV (Table 1). The number of migratory birds flying to Hawaii each year is large (Table 1) and most of these birds migrate to Hawaii during the late portion of the peak WNV-transmission period, suggesting the risk could be substantial. However, it is unclear whether a viremic bird could survive the > 2500 mile migration. Surveillance for migratory birds carrying active infections have yielded negative results so far, despite over 16,000 birds tested [Marra et al., unpublished data; McLean et al., unpublished data]. If subsequent research shows this to be an important pathway for introducing WNV to Hawaii, the best management approach would be to keep vector populations low near arrival areas for migratory birds.

We have quantitatively assessed the risk of West Nile virus being introduced to Hawaii by several different pathways. Although some of our analyses did not incorporate error estimates in our parameters, our qualitative conclusions are nonetheless robust to significant deviations. Our results suggest that there is substantial risk from human transported mosquitoes and birds, and we have suggested actions that should be taken as soon as possible to reduce these risks.

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