An outbreak of measles on the island of Ponape led to a study of the epidemiology of the disease in the United States Trust Territory of the Pacific Islands. The authors' report on the critical number of susceptibles necessary for secondary transmission, the time intervals needed for accumulation of susceptibles, and a mathematical model used to predict such intervals.

THE EPIDEMIOLOGY OF MEASLES IN THE U.S. TRUST TERRITORY OF THE PACIFIC ISLANDS

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Introduction

HISTORICALLY, measles in islands of the Pacific Ocean has been associated with devastating epidemics. In 1848 in Hawaii, 10,000 natives, about 10 per cent of the population, died during an epidemic.[1,2,3] In 1861 on Aneityum in the New Hebrides, the population was reduced by about 60 per cent in a measles epidemic.[4] In 1875 in Fiji, 20,000 natives, 20 to 25 per cent of the population, died of measles.[5] In 1907, again in Fiji, 6 per cent of 30,000 cases died, and in 1911 on Rotuma 16 per cent of the population died of measles.[6]

Even in relatively recent years, measles has been epidemic in the Pacific. In 1936 measles caused 100 deaths and 14,282 cases in the Gilbert Islands,[7] and in 1937 in Hawaii, there were 205 deaths for 13,680 cases of measles.[8] In 1946 in the British Islands of the South Pacific, there were 1,000 deaths for 15,000 to 20,000 cases[9] and in 1949 on Guam there were 13 deaths for 5,022 cases of measles.[10] Mortality has continued to decline, and now deaths due to measles are relatively uncommon. For example, in 1955 and 1956 there were 12,607 cases in Hawaii with only three deaths reported.

The epidemiology of measles on Pacific islands in the pre-jet airplane era was generally characterized by sporadic epidemics among accumulated susceptible populations. With extensive travel in the Pacific and repeated introductions of measles virus, few island populations are "virgin soil" for measles. Nevertheless, island communities do accumulate susceptible children and young adults because of their relative isolation.[11,12,13] Thus the epidemiology of measles in the Pacific is changing because of the small size of island populations, their relative isolation, conditions of transmission peculiar to these populations, and the repeated introductions of measles virus. Because of these susceptible groups and the historical severity of the disease, outbreaks of measles in the Pacific islands cause concern even now. However, documentation of the ecology of measles in the Pacific is limited. This paper describes an outbreak* of measles and a survey to measure measles antibodies in residents of Ponape Island in the United States Trust Territory of the Pacific Islands during July and August of 1968. A model, based on the data obtained, of measles transmission is also presented to elucidate the ecology of measles in that area.

Description of the Area

The Trust Territory of the Pacific Islands includes 97 inhabited islands, 700 square miles of land, located in an ocean area of three million square miles. The total population is 91,448 (1967). As shown in Figure 1, the islands are divided into four geographic groups: a northern group, the Marianas; an eastern group, the Marshalls; a central group, the Eastern Carolines; and a western group, the Western Carolines. These geographic areas are further divided into six administrative and health districts: The Marianas District, the Marshalls District, the Yap and Palau Districts encompassing the Western Carolines, and the Truk and Ponape Districts encompassing the Eastern Carolines. District populations range from 6,761 (Yap) to 25,107 (Truk).

Ponape is a mountainous volcanic island at 7° N latitude, twenty-four miles in diameter, surrounded by mangrove swamp, lagoon, and reef. The island is divided into six municipalities (Figure 2 and Table 1). Kolonia Municipality includes the island's only town, Kolonia, which is the site of the district hospital,

* Defined as the occurrence in a community of a group of similar illnesses clearly in excess of normal expectancy and derived from a common or propagated source (Control of Communicable Disease in Man, Ed. J. E. Gordon, 10th Edition, 1965, p. 15).

Figure 1

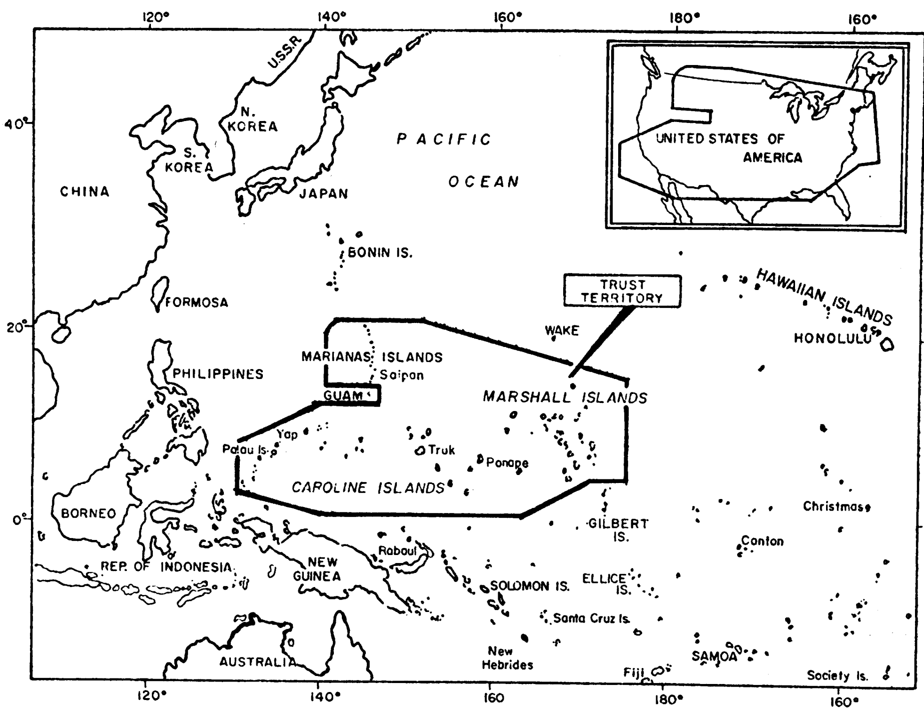


Figure 2—Ponape Island, Eastern Carolines

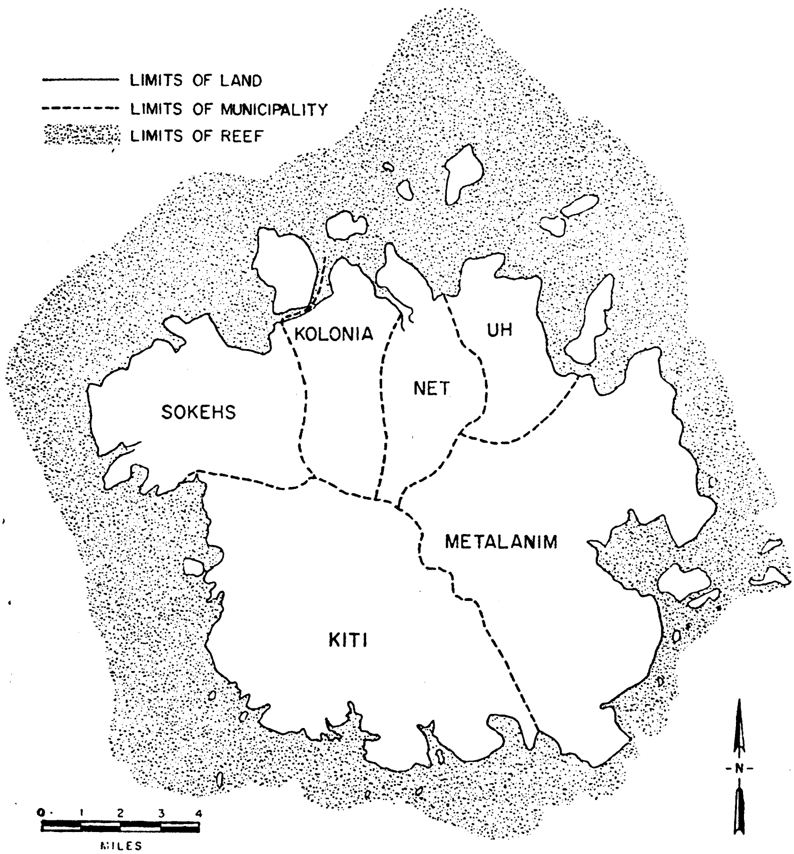


Table 1—Distribution of measles cases by municipality, Ponape Island, Eastern Carolines, July 1 to August 23, 1968

Municipality	No. of cases	Population	Cases per 1,000
Kolonia	53	2,991	18.1
Sokehs	16	2,055	7.8
Net	5	1,368	3.7
Metalanim	9	2,571	3.5
Uh	2	1,470	1.4
Kiti	1	2,369	0.4
Unknown residence	7	—	—
Total	93	12,824	7.3

outpatient clinic, and public health office. The people of Ponape live in family units scattered throughout the island. Travel to the district is limited. A seventeen-seat amphibian plane makes two flights a week from Truk to Ponape, and a field ship visits approximately twice a month. Travel within the district is limited; a field ship stops at each island at least every two to three months. Travel on Ponape Island is by foot or boat except in Kolonia Town, where there are roads for bicycles and automobiles.

The inhabitants of Ponape are primarily Micronesians, who are short and have light brown skin; they are culturally and racially derived from Indonesians, Polynesians, and Melanesians. Their language has a Malayo-Polynesian root. The basic social unit is the household, comprising an extended family living in thatched, one-room, open houses. The household is headed by a male, is relatively self-sufficient, and consumes what it produces. Land is essential to the family since the subsistence-level, household economy depends primarily on taro, breadfruit, coconut, sweet potato, and to a lesser extent, fish. There are few natural resources for economic development. Copra is the primary money-producing export. There is a small community of Polynesians living near the town of Kolonia.

Methods

Epidemiologic Data

Geographic data, population figures, and measles morbidity in the United States Trust Territory of the Pacific Islands were obtained from the Director of Public Health of the Trust Territory. A census completed in 1967 provided detailed population data.

In this study the criteria for being counted as a case of measles were fever and rash as described in Results. Ninety-three cases fulfilled these criteria. They were found in a review of hospital and clinic records and by radio announcements requesting interviews with all patients.

Sera for measles antibodies were obtained from 7.0 per cent of the population in three outlying municipalities on Ponape—Uh, Kiti, and Metalanim (Figure 2). When sera were collected, these three municipalities had had only a few cases of measles and no measles vaccinations. The other three municipalities of Ponape Island—Sokehs, Net, and Kolonia—were excluded from the survey because they had had measles or extensive measles vaccination programs by the time sera were obtained. Blood was drawn from persons randomly selected from the crowds waiting at each vaccination station in the districts of Kiti, Uh, and Metalanim. Any person who was known to have had measles during the current outbreak or who had been vaccinated previously at another station was excluded from the survey.

Laboratory Procedures

Sera were frozen on the day of collection and subsequently shipped on dry ice to the Viral Exanthem Units, National Communicable Disease Center (NCDC), for testing. Survey sera were screened for measles hemagglutination inhibition (HI) antibodies at a single dilution of 1:8 by standard procedures. Results were reported as positive (titer equal to or greater than 1:8) or negative (titer less than 1:8). By the method used at NCDC, persons with titers of less than 1:8 (negative) may be considered non-immune and all others immune due to past experience with measles infection or immunization.

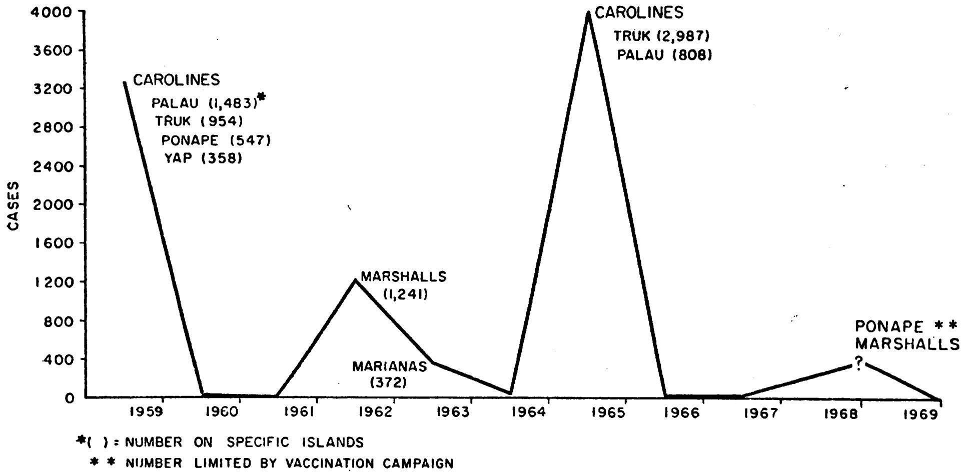
Results

Measles morbidity in the entire Trust Territory of the Pacific Islands is shown by year in Figure 3 and by season in Figure 5. In Ponape District, measles had not been reported since 1959, when there was an outbreak of 547 cases. However, outbreaks have been reported in other districts as recently as 1965. Measles vaccine had not been distributed on Ponape before the present outbreak.

The first case of measles in this outbreak began with a rash on July 1, 1968. Between July 1 and August 23, 1968, when the study was terminated, a total of 93 cases were identified on Ponape Island. Review of hospital and clinic records turned up 45 cases; 48 more cases were identified as a result of radio requests for interviews with all families having cases of measles.

Clinically, the illness was characterized by fever, conjunctivitis, and a red,

Figure 3—Reported measles cases, by year and area Trust Territory of the Pacific Islands, 1959-1969



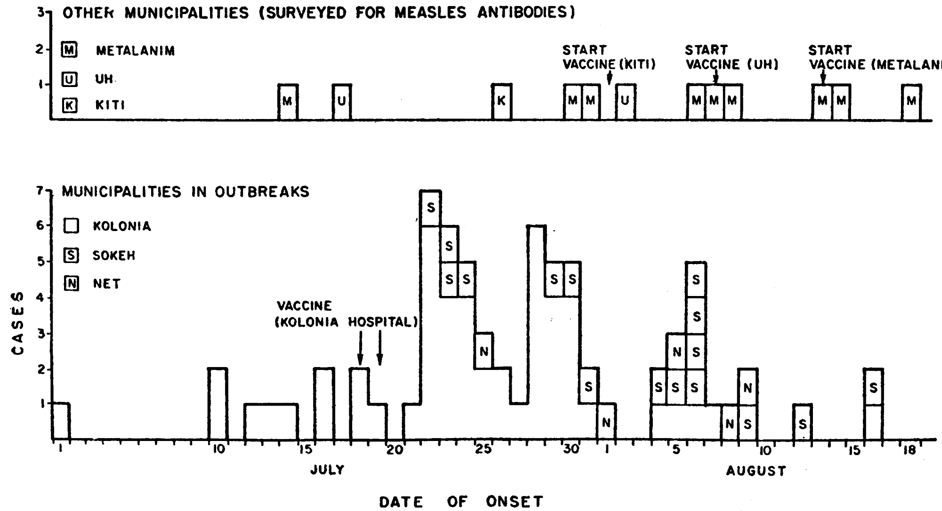
macular rash that began on the face and spread to the trunk and extremities, evolving to a brown desquamating phase over a 5–10 day period. Thirty-eight patients when seen gave a characteristic history and had the brown desquamating rash, and twenty-one cases gave appropriate histories but had no rash when seen by one of the authors (KLG). Thirty-four cases were diagnosed by other physicians in the outpatient clinic at Kolonia. Ten of the 93 patients were hospitalized for complications, the most common being pneumonia. One four-year-old girl developed probable encephalitis with marked lethargy and recurrence of fever on the 12th day after onset of rash. There were no deaths known to be due to measles. Measles HI antibody titers in acute and convalescent sera from seven cases of measles or suspected measles confirmed the diagnosis.

Epidemic curves by area are shown in Figure 4. The first recognized case was in a four-year-old girl who resided in Kapinga Village, a section of Kolonia Town. Her rash appeared on July 1, 1968. The probable source of her infection was her 10-year-old brother, who had been in Guam for a cardiac evaluation from May 20 to approximately June 3. One to two weeks after his return to Ponape, he had a moderately severe respiratory infection with fever. Both he and his mother denied observing any rash and denied any history of measles. However, a measles HI antibody titer of 1:256 was measured in each of paired sera taken twelve and twenty-five days after the approximate time of his febrile illness. These high titers are suggestive of recent measles infection. Other than his brother, no relatives, neighbors, or friends of the index patient were known to have traveled to or from Ponape during June 1968.

The geographic distribution of cases is shown in Table 1 and Figure 4. Most of the patients resided in the municipality of Kolonia. Only one other island in the district reported any cases: a resident of Kusaie Island developed measles on July 31, 1968, after visiting a field ship from Ponape.

The age distribution of patients on Ponape is shown in Table 2; 95.7 per cent were 9-years-old or younger. The group 4-years-old and younger had the highest attack rate.

Figure 4—Measles cases, by date of onset and area, Ponape Island, Eastern Carolines, 1968



Sera were obtained from 357 persons, or 7.0 per cent of the population 2-years-old and older, of three outlying municipalities—Uh, Kiti, and Metalanim. The results are shown by area in Table 3 and by age in Figure 6. The proportion of persons with a measles HI antibody titer of 1:8 or higher in three broad age groups were as follows: 38.5 per cent of 52 sera from children 2- to 4-years-old; 55.3 per cent of 85 sera from children aged 5- to 9-years-old; 96.8 per cent of 220 sera from persons 10 and older. However, the age-antibody distribution curve (Figure 6) can be extended to the under-2 age group for an estimate of the per cent immunes in the group 9-years-old and younger (rather than the group 2- to 9-years-old). Thus, about 40 per cent of the group 9-years-old and younger were immune, with about 60 per cent susceptible. The sharpest rise in proportion of immunes occurred at ages 9- to 10-years-old.

Epidemic control measures consisted of an immunization campaign in the various municipalities, as shown in Figure 4. On the basis of age distribution of cases, children 9 months through 14-years-old were given live virus measles vaccine. As shown in Table 4, 74.6 per cent of the target population received vaccine. The effect of the campaign on the outbreak is shown in Figure 4. Initial vaccinations were given at Kolonia Hospital to residents of Net, Sokehs, and Kolonia; after 12 days the number of new cases in Kolonia decreased. No cases were identified in susceptibles who

Figure 5—Reported cases of measles by month, Trust Territory of the Pacific Islands, 1959-1967

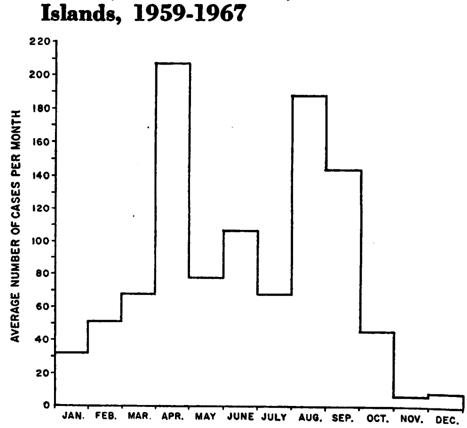


Table 2—Distribution of measles cases by age, Ponape Island, Eastern Carolines, July 1 to August 23, 1968

Age group	0–4	5–9	10–14	15–19	45	Unknown	Total
Number of cases	69	20	1	0	1	2	93
Per cent of all cases	74.2	21.5	1.1	0	1.1	2.2	100
Cases per 1,000	30.7	9.2	–	–	–	–	7.3

Table 3—Distribution of survey sera by municipality Ponape Island, Eastern Carolines, 1968

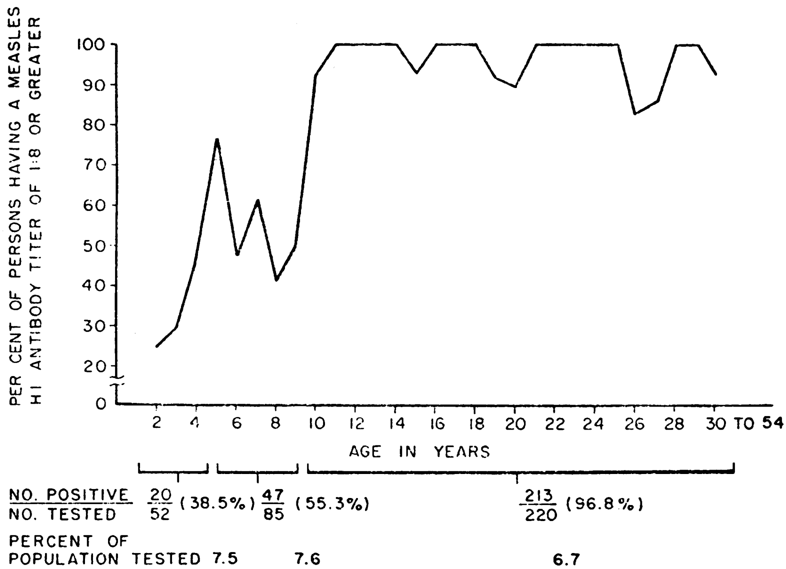
Municipality	Number of sera	Population 2–54 years old	Per cent of population sampled	Number of sera positive	Per cent of sera positive
Uh	96	1,243	7.7	67	69.8
Kiti	110	1,749	6.3	84	76.4
Metalanim	151	2,103	7.2	129	85.4
Total	357	5,095	7.0	280	77.1

were vaccinated prior to or within three days after exposure. Cases thereafter appeared primarily in adjacent municipalities where vaccination coverage was less complete or began after August 1.

Discussion and Mathematical Analysis

The age of abrupt increase in immunes on Ponape is older than in larger populations, such as mainland United States; it is comparable to that in small populations.[14-19] The data indicate that the population of Ponape is not "virgin ground" for measles. There is no abrupt increase in the proportion of immunes in any particular age group of children born since 1959. These findings suggest that the population of Ponape was repeatedly exposed to measles virus after 1959, but that secondary transmission was limited and did not affect all susceptibles in the population. If a discrete epidemic affecting all susceptibles had occurred after 1959, the proportion of immunes would have increased abruptly in some age group under 9 years and remained high in older age groups. Similar observations have been used elsewhere to date the most recent outbreak in an island population, as in Tahiti.[11,12] It is unlikely that measles has become an endemic, sporadic disease on Ponape in view of Rosen's observation that measles did not persist indefinitely in an island population of 35,000 or less.[11] However, repeated introductions of measles virus with limited secondary transmission would account for the immunity pattern in the group 9-years-old and younger. This secondary transmission would be limited if the number of susceptibles on Ponape were under that critical level necessary to sustain secondary transmission and an outbreak. Despite measles activity after 1959, not until the proportion of susceptibles reached 60 per cent of the group 9-years-old and younger was there an outbreak. Thus, on Ponape the critical number of susceptibles necessary to sustain secondary transmission and an outbreak

Figure 6—Age distribution of persons with measles HI antibody titer of 1:8 or greater, three municipalities of Ponape Island, Eastern Carolines, 1968



is probably 60 per cent of those 9-years-old and younger.

With this information, the interval between outbreaks of measles on Ponape can be predicted, as follows: The population of children 9-years-old and younger on Ponape Island is 4,412. Sixty per cent$\times$4,412=2,647, which is the critical absolute number of susceptibles necessary to sustain secondary transmission and an outbreak. The rate at which susceptibles are added to this population is 440 per year (born and surviving). If there had been no measles activity after 1959, the number of years required to accumulate this critical number of susceptibles would have been 2,647$\div$440 per year=6.0 years. However, the survey data show that 40 per cent of the group 9-years-old and younger were immune because of limited, unsustained transmission that did not affect all susceptibles. These repeated introductions of measles virus with limited transmission prolongs the period of time required to accumulate the critical number of susceptibles. This added interval is 40 per cent$\times$2,647 or 1,058$\div$440 per year=2.4 years. In other words it takes 2.4 years to accumulate an additional 1,058 susceptibles (removed by limited, inter-epidemic transmission) needed to reach the critical number of susceptibles. Thus, the predicted total length of time required to accumulate the critical number of susceptibles is 6.0 years+2.4 years=8.4 years. These two steps can be combined into one simple equation: $I = 2{,}647 \div R + 1{,}058 \div R = 3{,}705 \div R$ where

Table 4—Distribution of measles vaccine by age, Ponape Island, Eastern Carolines, 1968

Age in years	Number vaccinated	Population	Per cent vaccinated
9 mos.–4	1,435	1,961	73.2
5–9	1,578	2,163	72.9
10–14	1,187	1,506	78.8
Total	4,200	5,630	74.6

I is the predicted interval between outbreaks and R is the rate of accumulation of susceptibles. Thus, 8.4 years is the observed length of time between outbreaks on Ponape Island (1959–1968) as indicated by reported cases (Figure 3), as well as by survey results dating the last outbreak in 1959 (Figure 6).

The population of the outer islands of Ponape District were not included in the analysis for several reasons. Since these outer islands are rather remote, their populations are not comparable to the population at risk on Ponape Island. Furthermore, survey sera for measles antibodies were not obtained in the outer islands.

This description of the epidemiology of measles on Ponape Island can be extended to other districts in the Trust Territory of the Pacific Islands by making two assumptions:

First Assumption: For small dispersed island populations, as in districts of the Trust Territory, the critical level of susceptibles necessary to sustain secondary transmission and a measles outbreak depends on the density of susceptibles rather than the proportion of susceptibles in the population. In a relatively dispersed population with dispersed susceptibles, the total population around the susceptibles has little influence on transmission. For example, if the population of an island, islands, or zone of risk were 5,000, the proportion of susceptibles would be 60 per cent. If the population were 15,000, the proportion of susceptibles would be 20 per cent. Except as a determinant of the rate of accumulation of susceptibles, the size of the population matrix in which susceptibles live, and thus the proportion of susceptibles, is not critical in this model. However, a simple calculation of susceptibles per square mile is inadequate for several reasons. Many islands of the Trust Territory are uninhabited. The amount of travel, style of living, the number of islands, and distance between them also are factors affecting transmission. For the equation used in this model, these complex factors are combined into a single theoretical parameter which is here called "zone of risk." Then the measure of density of susceptibles can be expressed as the critical number of susceptibles in a zone of risk rather than in a square mile.

Second Assumption: Conditions for measles transmission in other districts of the Trust Territory resemble those on Ponape. Outbreaks in other districts would then be determined by the same critical number of susceptibles in the zone of risk for each district.

Based on the first assumption the simple formula used earlier to calculate the interval between outbreaks can be generalized as follows:

$$I = \frac{Z \times P}{R}$$

where I = the interval between outbreaks in a district
R = rate of accumulation of susceptibles in a district
P = the absolute critical number of susceptibles necessary for sustained secondary transmission in a zone of risk
Z = the zone of risk (no units)

Z can be calculated for Ponape since I, P, and R are known independently by observation.

$$8 \text{ years} = \frac{(Z)\ (3{,}705)}{440 \text{ per year}}$$

$$Z = 0.95 \text{ or about } 1.0.$$

Thus, for districts which have zones of risk comparable to Ponape, the intervals between epidemics are determined only by the rate of accumulation of susceptibles (R) and an absolute critical number of susceptibles (P). In terms of this equation, the second assumption means that Z equals one for other districts. It also means that the critical number of susceptibles in the zone of risk for other districts is the same as for Ponape, i.e., 3,705 as shown in Table 5.

The parameter Z can be considered as a constant characteristic of a district in this model. For a district in which the simple relation P/R describes the interval between outbreaks, Z is equal to one. For a district with a greater density of susceptibles than Ponape, the critical number for sustaining an outbreak will be correspondingly smaller. Z indicates how much smaller this critical number will be relative to Ponape. In other words, for a given district it determines the degree to which the simple relation $I = P/R$ is untrue. For dense urban populations Z becomes small, whereas for dispersed populations Z approaches unity.

From these assumptions and this model, the interval between outbreaks of measles in districts of the Trust Territory can be calculated theoretically with the equation. The predicted and observed intervals between outbreaks are shown in Table 5. In all districts except Palau the predicted interval is close to the observed interval. There is a good explanation for the one exception. Residents of Palau generally live in crowded, i.e., "urban" areas, and the density of the population (and susceptibles) is higher than in other districts. A high population density facilitates measles transmission. Therefore on Palau, the critical number of susceptibles and the time interval necessary for their accumulation is probably less than on Ponape. For these reasons the second assumption does not apply, i.e., the constant Z does not equal 1.0 for Palau, and data are not available to calculate directly this value of Z.

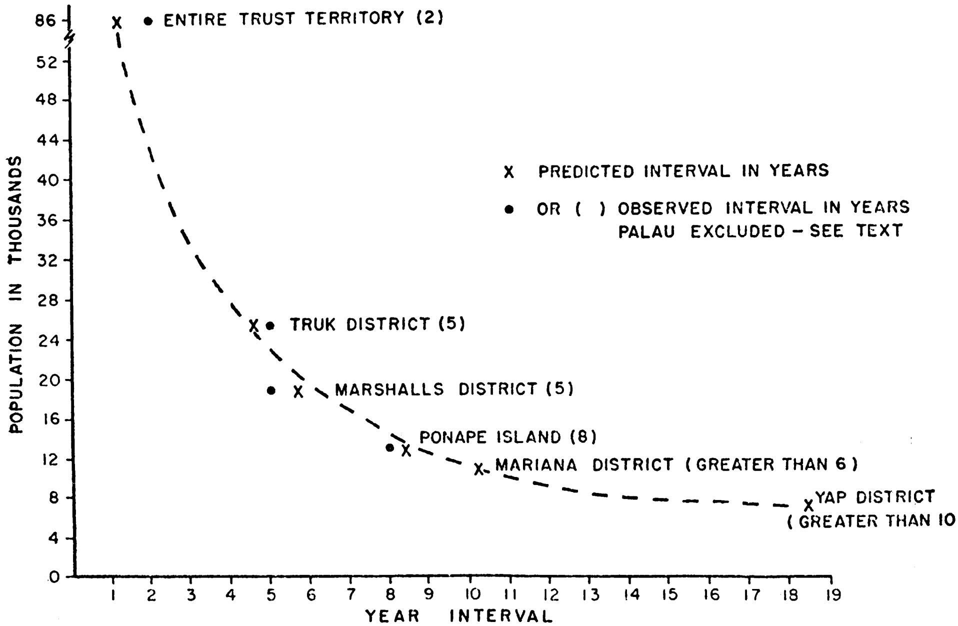
However, let us assume that Palau resembles another relatively urban island community, Hawaii, in terms of these density factors. Its constant Z can be calculated as follows from records of the Hawaii Department of Health.[20] In Hawaii the average interval between outbreaks (I) is 2 years and R is 17,242 (1- to 14-years-old, 1960 census). From a survey of history of measles infection in the population of that state just after the 1965 outbreak, the critical proportion of susceptibles is at least 40 per cent of the age group 1–14 years, a finding consistent with the generally

Table 5—Predicted and observed intervals between outbreaks of measles in the U.S. Trust Territory of Pacific Islands

Area and population	Rate of accumulation of susceptibles (R)	Interval between outbreaks of measles: Predicted (3,705 ÷ R)	Interval between outbreaks of measles: Observed
Ponape Island* (12,824)	440 per year	8.4 years	8 years (9 year cycle)
Marshalls District (18,925)	647 per year	5.7 years	5 years (6 year cycle)
Truk District (25,107)	806 per year	4.6 years	5 years (6 year cycle)
Yap District (6,761)	200 per year	18.5 years	Greater than 10 years
Mariana District (10,986)	362 per year	10.2 years	Greater than 6 years
Palau District (11,365)	384 per year	4.1 years)†	5 years (6 year cycle)
Entire Trust Territory* (85,968)	2,839 per year	1.3 years	2 years (3 year cycle)

* These figures exclude the population (5,480) of the outer islands of Ponape District. See text for explanation.
† See text for explanation.

Figure 7—Intervals between measles outbreaks in the U.S. Trust Territory of the Pacific Islands



quoted figure.[17,21] This per cent represents a critical absolute number of susceptibles (P) in Hawaii of 80,362. Substituting, Z for Hawaii can be calculated.

$$I\ (\text{Hawaii}) = \frac{Z \times P}{R}$$

$$2\ \text{years} = \frac{Z \times 80{,}362}{17{,}242}$$

$$Z = 0.43\ (\text{Hawaii})$$

Substituting this value of Z for Palau the interval between outbreaks can be correctly calculated.

$$\text{Corrected I (Palau)} = \frac{0.43 \times 3{,}705}{384} =$$

4.1 years, which is the theoretically predicted interval on Palau, the observed interval is 5 years. With these additional considerations the calculations for Palau are consistent with the basic hypothesis.

Thus, the intervals between outbreaks of measles in districts of the Trust Territory can be predicted from the rate of accumulation of susceptibles and a critical density of susceptibles, which in turn is determined by many complex factors affecting transmission of measles virus. The rate of accumulation of susceptibles, and therefore the interval between outbreaks, is then proportional to the size of the population in a district. This relationship is shown in Figure 7. Districts with large populations and high birth rates have relatively short intervals between outbreaks. If the entire Trust Territory is considered as a whole, there is a two-year interval between outbreaks (a three-year cycle). However, this cycle results from the superimposition of longer cycles for each district. For conditions of transmission similar to those in Micronesia, the population size at which measles has a 3-year cycle would probably be about 40,000 to 50,000, as shown in Figure 7.

A measles control program for the Trust Territory could be based on these epidemiologic findings. Logistics in the

Trust Territory would make annual measles vaccination campaigns in each district very costly. However, rotating vaccination campaigns in each district every 4 to 5 years would probably eliminate outbreaks despite repeated introductions of measles virus. Based on the Ponape experience, vaccination of 75 per cent of the population 9 years old and younger would probably prevent outbreaks in a district.

Summary

Between July 1 and August 23, 1968, an outbreak of 93 cases of measles was reported on the island of Ponape in the Eastern Carolines. Ninety-five and seven-tenths per cent of the cases were 9-years-old or younger. Ten cases were hospitalized and one case developed encephalitis. There were no deaths. The outbreak was limited by vaccinating 74.6 per cent of the group 9 months to 14-years-old. Sera for measles HI antibodies were obtained from 7.0 per cent of the population of three outlying municipalities relatively unaffected by the outbreak. Ninety-six and eight-tenths per cent of persons 10 years and older were immune whereas 40 per cent of persons 9 years and younger were immune. Analysis of these findings with population data indicate: (1) An outbreak of measles in 1959 affected all susceptibles on Ponape Island. Measles has been repeatedly introduced into Ponape Island since 1959, but secondary transmission was limited and did not result in an outbreak affecting all susceptibles. (2) The critical number of susceptibles necessary to sustain secondary transmission and an outbreak on Ponape Island is about 60 per cent of the group 9-years-old and younger. (3) The time intervals between outbreaks on Ponape Island and districts of the Trust Territory depend on the rate at which susceptibles accumulate. When the critical number of susceptibles is reached, an outbreak occurs. This interval between outbreaks ranges from 4 or 5 years for districts with large populations to over 10 years for districts with small populations. (4) A simple mathematical model, based on the concept of a critical density of susceptibles, was used to predict correctly the intervals between outbreaks of measles in the Trust Territory. (5) A measles control program based on rotating vaccination campaigns every 4 to 5 years in each district of the Trust Territory would probably prevent sustained secondary transmission and outbreaks of measles.

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This paper was submitted for publication in May, 1970.

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