# Supporting Information

## Dean et al. 10.1073/pnas.1715640115

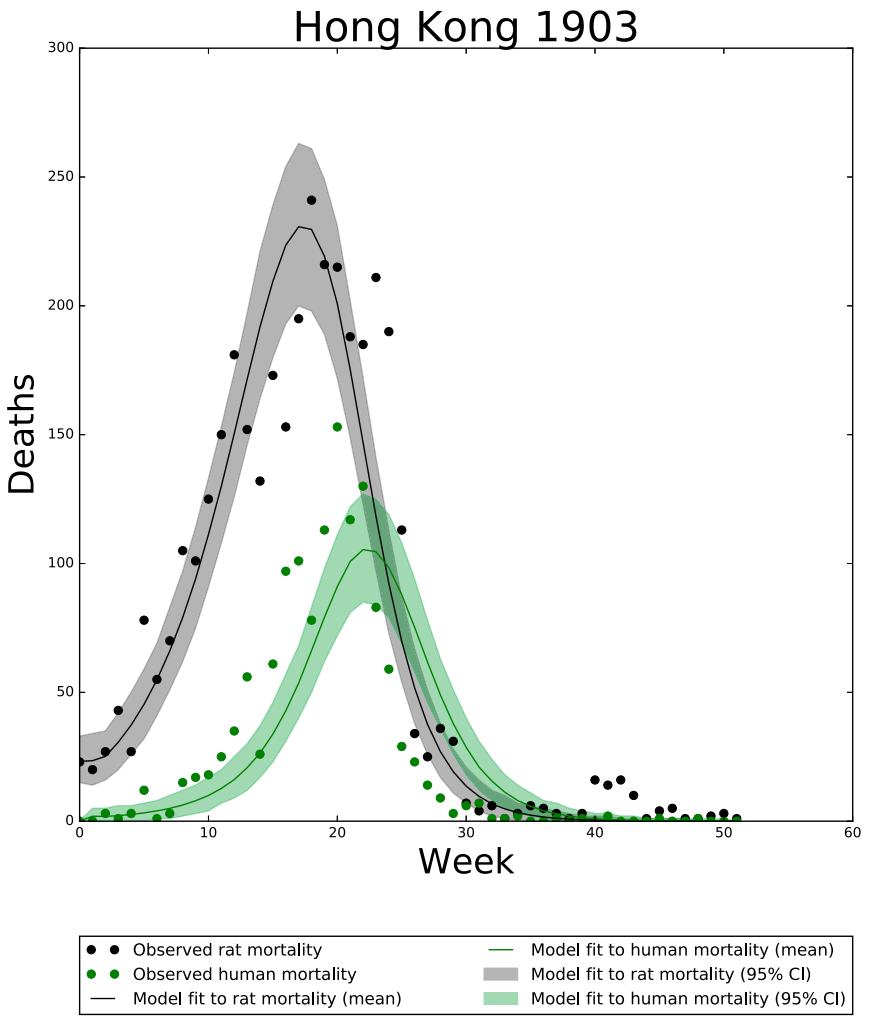


**Fig. S1.** Fit of the rat–flea model to observed rodent and human mortality during the 1903 plague outbreak in Hong Kong. The observed rat mortality (black dots), the observed human mortality (green dots), and fit (mean and 95% credible interval) of the rat model for plague transmission to both the rat (black) and human (green) mortality. The mortality peak for humans from the model is delayed compared with the observed data. However, the model captures the dynamics of the rat mortality and the relationship between the epizootic and the epidemic well by showing the characteristic higher rat mortality and the delay in the onset of the epidemic in humans.

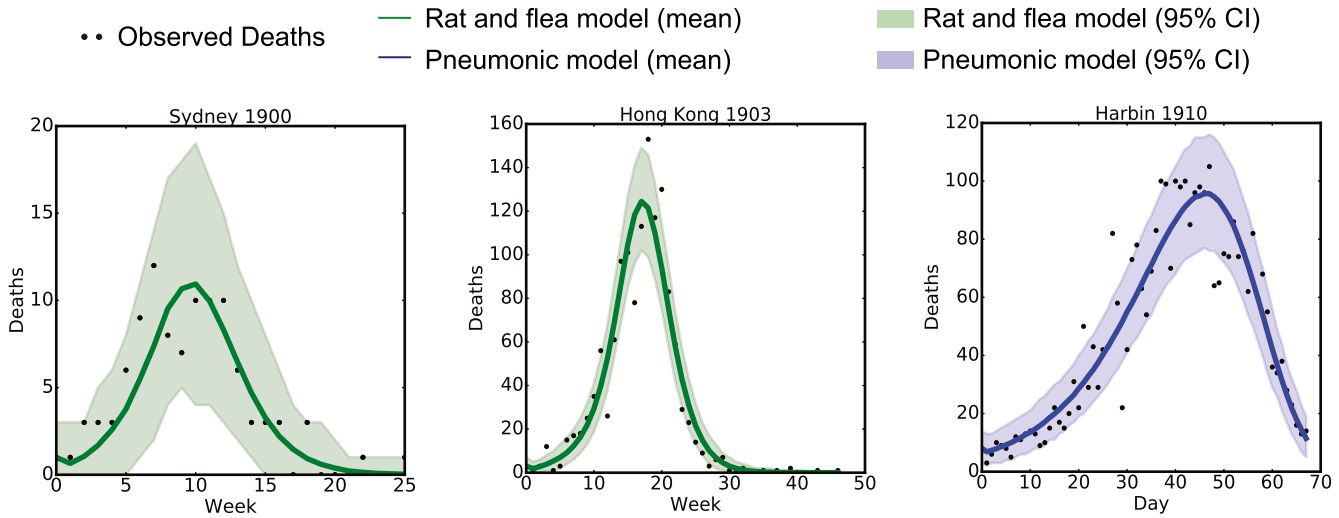


**Fig. S2.** Fit of the pneumonic and rat–flea models of plague transmission to mortality during Third Pandemic outbreaks. The observed human mortality data (black dots) for plague outbreaks and the fit (mean and 95% credible interval) of the relevant model for plague transmission in each plague outbreak: pneumonic (blue) and rat–flea (green). Both the rat–flea model of plague transmission and the pneumonic plague transmission are well capable of fitting observed human mortality patterns for plague outbreaks that these models describe.

**Table S1. Summary of the Third Pandemic mortality data**

| Location | Date, MM/YYYY | Population | Recorded deaths | Transmission mode | Ref. |
|---|---|---|---|---|---|
| Sydney, Australia | 02/1900–08/1900 | 400,000 | 103 | Rat–flea | 1 |
| Hong Kong, China | 01/1903–12/1903 | 250,000 | 1,308 | Rat–flea | 2 |
| Harbin (Fuchiatien), China | 12/1910–02/1911 | 25,000 | 3,223 | Pneumonic | 3 |

The present-day location, dates (month/year), preplague population size, and recorded plague deaths, and known transmission mode for three plague outbreaks during the Third Pandemic.

1. Cumpston JHL, McCallum F (1926) *The History of Plague in Australia, 1900–1925* (H. J. Green Govt Printer for Commonwealth of Australia Dept Health, Melbourne).
2. Hunter W (1904) *A Research into Epidemic and Epizootic Plague* (Noronha and Company, Hong Kong).
3. Anonymous (1912) *Report of the International Plague Conference Held at Mukden, April, 1911*, ed Strong RP (Bureau of Printing, Manila, Philippines).

**Table S2. Initial conditions for three SIR models of plague transmission**

| Parameter | Value | Definition |
|---|---|---|
| Human ectoparasite model | | |
| $S_h(0)$ | $U(0.001, 1)$*population size | Initial susceptible humans |
| $I_{low}(0)$ | $U(1, 10*D_h(0))$ | Initial infected (low) humans |
| $I_{high}(0)$ | $2*D_h(0)$ | Initial infected (high) humans |
| $R_h(0)$ | 0 | Initial recovered humans |
| $D_h(0)$ | Observed deaths at $T = 0$ | Initial dead humans |
| Pneumonic plague model | | |
| $S_h(0)$ | $U(0.001,1)$*population size | Initial susceptible humans |
| $I_h(0)$ | $U(1, 10*D_h(0))$ | Initial infected humans |
| $D_h(0)$ | Observed deaths at $T = 0$ | Initial dead humans |
| Rat–flea model | | |
| $S_r(0)$ | $U(0.001, 1)$*population size | Initial susceptible rats |
| $I_r(0)$ | $U(1, 15*D_h(0))$ | Initial infected rats |
| $R_r(0)$ | 0 | Initial recovered rats |
| $D_r(0)$ | 0 | Initial dead rats |
| $S_h(0)$ | $S_r(0)$ | Initial susceptible humans |
| $I_h(0)$ | $1.5*D_h(0)$ | Initial infected humans |
| $R_h(0)$ | 0 | Initial recovered humans |
| $D_h(0)$ | Observed deaths at $T = 0$ | Initial dead humans |
| $H(0)$ | $K_f$ | Initial fleas on host |
| $F(0)$ | $K_f*D_h(0)$ | Initial free infected fleas |

Single numbers are fixed values and distributions ($U$ = uniform) are priors.

**Table S3. Initial parameter values and posterior estimates for the rat–flea model fitted rat and human mortality in Hong Kong**

| Parameter | Parameter value/prior distribution | Posterior estimate, mean [95% highest posterior density interval] |
|---|---|---|
| $S_h(0)$ | $S_r(0)$ | Fixed |
| $I_h(0)$ | 5.0 | Fixed |
| $R_h(0)$ | 0 | Fixed |
| $D_h(0)$ | Observed deaths at $T = 0$ | Fixed |
| $\beta_h$ | $U(0.001, 1)$ | 0.11 [0.10, 0.12] |
| $S_r(0)$ | $U(0.001, 1)$**population size* | 0.018 [0.017, 0.018] * 250,000 |
| $I_r(0)$ | $U(1, 23)$ | 22.8 [22.6, 23] |
| $R_r(0)$ | 0 | Fixed |
| $D_r(0)$ | Observed deaths at $T = 0$ | Fixed |
| $\beta_r$ | $U(0.001, 1)$ | 0.053 [0.053, 0.053] |

Single numbers are fixed values, and distributions ($U$ = uniform) are priors.

**Table S4. Posterior means and 95% highest density posterior intervals for estimated parameters in three plague models for Second and Third Pandemic outbreaks**

| Location | Model | Population at risk (proportion) | Initial infected $[I_{low}(0), I_h(0), I_r(0)]$ | Transmission rate $(\beta_{low}, \beta_{high}, \beta_p, \beta_r, \beta_h)$ |
|---|---|---|---|---|
| Givry (1348) | EP | 0.75 [0.69, 0.81] | 2.21 [2, 2.61] | 0.04 [0.02, 0.05] |
| | | | | 0.39 [0.32, 0.53] |
| | PP | 0.42 [0.38, 0.45] | 1.85 [1.41, 2.32] | 0.44 [0.43, 0.44] |
| | RP | 0.73 [0.64, 0.81] | 28.81 [26.60, 29.99] | 0.06 [0.06, 0.06] |
| | | | | 0.19 [0.18, 0.2] |
| Florence (1400) | EP | 0.36 [0.35, 0.36] | 79.65 [78.99, 80] | 0.049 [0.04, 0.05] |
| | | | | 0.32 [0.31, 0.38] |
| | PP | 0.17 [0.17, 0.17] | 79.79 [79.39, 79.99] | 0.42 [0.42, 0.42] |
| | RP | 0.19 [0.19, 0.19] | 119.91 [119.76, 120.0] | 0.084 [0.083, 0.085] |
| | | | | 0.2 [0.199, 0.2] |
| Barcelona (1490) | EP | 0.28 [0.27, 0.28] | 8.68 [7.54, 9.97] | 0.032 [0.007, 0.05] |
| | | | | 0.49 [0.35, 0.67] |
| | PP | 0.14 [0.13, 0.14] | 9.90 [9.73, 10.0] | 0.43 [0.43, 0.43] |
| | RP | 0.14 [0.13, 0.14] | 14.95 [14.87, 15.0] | 0.08 [0.08, 0.08] |
| | | | | 0.2 [0.19, 0.2] |
| London (1563) | EP | 0.42 [0.41, 0.42] | 32.45 [29.68, 35.62] | 0.04 [0.04, 0.05] |
| | | | | 0.27 [0.26, 0.28] |
| | PP | 0.21 [0.20, 0.21] | 50.85 [48.81, 52.99] | 0.43 [0.43, 0.43] |
| | RP | 0.30 [0.30, 0.31] | 254.80 [254.43, 255] | 0.06 [0.059, 0.06] |
| | | | | 0.2 [0.2, 0.2] |
| Eyam (1666) | EP | 0.97 [0.92, 1.0] | 3.76 [3, 4.97] | 0.032 [0.01, 0.05] |
| | | | | 0.32 [0.2, 0.5] |
| | PP | 0.56 [0.48, 0.63] | 3.80 [3, 4.82] | 0.41 [0.41, 0.42] |
| | RP | 0.96 [0.90, 1.0] | 38.08 [29.53, 44.97] | 0.04 [0.04, 0.05] |
| | | | | 0.19 [0.18, 0.2] |
| Gdansk (1709) | EP | 0.93 [0.92, 0.94] | 51.3 [49, 54.6] | 0.049 [0.046, 0.05] |
| | | | | 0.28 [0.26, 0.3] |
| | PP | 0.46 [0.46, 0.47] | 79.11 [76.56, 81.95] | 0.42 [0.42, 0.42] |
| | RP | 0.92 [0.90, 0.93] | 734.48 [733.36, 735] | 0.04 [0.04, 0.05] |
| | | | | 0.2 [0.2, 0.2] |
| Stockholm (1710) | EP | 0.42 [0.41, 0.42] | 159.63 [153.01, 168.35] | 0.04 [0.03, 0.05] |
| | | | | 0.33 [0.30, 0.38] |
| | PP | 0.22 [0.21, 0.22] | 145.36 [139.14, 151.28] | 0.42 [0.42, 0.42] |
| | RP | 0.36 [0.35, 0.36] | 2,290.65 [2,282.25, 2,294.99] | 0.069 [0.069, 0.069] |
| | | | | 0.2 [0.2, 0.2] |
| Moscow (1771) | EP | 0.34 [0.34, 0.35] | 157.41 [150.41, 164.44] | 0.04 [0.04, 0.05] |
| | | | | 0.34 [0.32, 0.39] |
| | PP | 0.17 [0.17, 0.18] | 148.31 [144.46, 152.12] | 0.43 [0.43, 0.43] |
| | RP | 0.20 [0.20, 0.21] | 659.86 [659.57, 660.0] | 0.069 [0.069, 0.069] |
| | | | | 0.2 [0.2, 0.2] |
| Malta (1813) | EP | 0.09 [0.09, 0.09] | 18.09 [16.47, 19.9] | 0.04 [0.04, 0.05] |
| | | | | 0.26 [0.23, 0.31] |
| | PP | 0.04 [0.04, 0.04] | 9.96 [9.90, 10.0] | 0.43 [0.43, 0.43] |
| | RP | 0.045 [0.044, 0.046] | 14.98 [14.939, 15.0] | 0.06 [0.06, 0.06] |
| | | | | 0.2 [0.2, 0.2] |
| Sydney (1900) | EP | 0.49 [0.003, 0.95] | 7.49 [5.48, 9.77] | 0.024 [0.0, 0.04] |
| | | | | 0.15 [0.0, 0.3] |
| | PP | 0.001 [0.0, 0.001] | 1.46 [1, 2.06] | 0.42 [0.41, 0.42] |
| | RP | 0.001 [0.0, 0.001] | 13.559 [10.637, 15.0] | 0.05 [0.04, 0.05] |
| | | | | 0.18 [0.14, 0.2] |
| Hong Kong (1903) | EP | 0.011 [0.011, 0.012] | 3.05 [3, 3.17] | 0.048 [0.044, 0.05] |
| | | | | 0.24 [0.22, 0.26] |
| | PP | 0.01 [0.01, 0.01] | 2.88 [2.41, 3.35] | 0.42 [0.42, 0.42] |
| | RP | 0.011 [0.009, 0.013] | 36.66 [27.63, 44.99] | 0.05 [ 0.05, 0.05] |
| | | | | 0.16 [0.13, 0.2] |
| Harbin (1910) | EP | 0.02 [0.02, 0.021] | 33.93 [27.09, 41.58] | 0.03 [0.01, 0.05] |
| | | | | 0.88 [0.76, 1.] |
| | PP | 0.12 [0.12, 0.13] | 16.99 [14.9, 18.98] | 0.48 [ 0.48, 0.48] |
| | RP | 0.11 [ 0.11, 0.11] | 119.25 [117.66, 119.99] | 0.14 [0.13, 0.14] |
| | | | | 0.19 [0.19, 0.2] |

Posterior estimates for initial conditions for different plague models and outbreaks. Models are designated as human ectoparasite (EP), primary pneumonic plague (PP), and rat and rat–flea (RP). Posterior estimates (mean [95% highest density posterior interval]) for the proportion of the initial population at risk, the initial number of infected [$I(0)$], and the transmission rate ($\beta$).

**Table S5. Comparison of transmission models and estimates for the basic reproduction number for different plague models and Third Pandemic outbreaks**

| Location | Model | BIC | ΔBIC | $R_0$ |
|---|---|---|---|---|
| Sydney (1900) | EP | 235 | 46 | 0.86 [0.86, 0.87] |
| | PP | 196 | **7** | 1.05 [1.05,1.05] |
| | RP | 189 | **0** | 1.36 [1.36,1.36] |
| Hong Kong (1903) | EP | 611 | 107 | 1.52 [1.52, 1.52] |
| | PP | 900 | 396 | 1.06 [1.06,1.06] |
| | RP | 504 | **0** | 1.41 [1.41,1.41] |
| Harbin (1910) | EP | 851 | 31 | 2.98 [2.98, 2.98] |
| | PP | 820 | **0** | 1.21 [1.21,1.21] |
| | RP | 1,606 | 786 | 3.62 [3.62,3.62] |

The models are designated as human ectoparasite (EP), primary pneumonic plague (PP), and rat and rat–flea (RP). Values in bold represent the best-fitting models that were within 10 points of the lowest BIC. The $R_0$ (mean [95% confidence interval]) was estimated for each model using the next-generation matrix.

**Table S6. Comparison of transmission models with different levels of underreporting**

| | | BIC | | |
|---|---|---|---|---|
| Location | Model | 10% underreporting | 25% underreporting | 50% underreporting |
| Givry (1348) | EP | **1,288** | **1,280** | 1,395 |
| | PP | 1,333 | 1,333 | **1,331** |
| | RP | **1,292** | 1,370 | 1,439 |
| Florence (1400) | EP | **2,729** | **2,876** | **3,392** |
| | PP | 4,668 | 4,928 | 5,877 |
| | RP | 10,568 | 11,264 | 12,752 |
| Barcelona (1490) | EP | **1,942** | **1,951** | **2,121** |
| | PP | 2,418 | 2,453 | 2,610 |
| | RP | 3,482 | 3,640 | 3,991 |
| London (1563) | EP | **1,582** | **1,577** | **1,575** |
| | PP | 4,630 | 4,629 | 4,629 |
| | RP | 4,256 | 4,954 | 6,743 |
| Eyam (1666) | EP | **1,176** | **1,175** | **1,243** |
| | PP | **1,174** | **1,174** | **1,238** |
| | RP | 1,210 | 1,228 | 1,304 |
| Gdansk (1709) | EP | **825** | **1,803** | No convergence |
| | PP | 3,817 | 3,817 | **3,817** |
| | RP | 2,176 | 4,447 | No convergence |
| Stockholm (1710) | EP | **718** | **709** | **688** |
| | PP | 2,180 | 2,109 | 2,110 |
| | RP | 1,238 | 1,612 | 2,759 |
| Moscow (1771) | EP | **3,916** | **3,916** | **3,931** |
| | PP | 6,790 | 6,790 | 6,790 |
| | RP | 17,604 | 22,612 | No convergence |
| Malta (1813) | EP | **2,760** | **2,775** | **2,864** |
| | PP | 3,653 | 3,850 | 4,244 |
| | RP | 6,632 | 6,953 | 7,656 |

The models are designated as human ectoparasite (EP), primary pneumonic plague (PP), and rat and rat–flea (RP). Values in bold represent the best-fitting models that were within 10 points of the lowest BIC.