Stochastic Simulation of COVID-19 Vaccine Efficacy and Uncertainty Analysis

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Introduction

The efficacy of COVID-19 vaccines has been extensively studied through clinical trials. This study uses stochastic simulations to analyze the placebo and treatment arms of three major COVID-19 vaccines: BioNTech/Pfizer, Moderna, and AstraZeneca/Oxford. Our objectives include:

- Simulating the placebo arms of the vaccine trials.
- Estimating the number of infections for each vaccine group.
- Calculating vaccine efficacy and uncertainty.
- Comparing simulated results with published trial data.

Methodology

Data Extraction

Clinical trial data from publications were extracted for placebo and vaccination arms. Key parameters include the number of participants (N), surveillance time (T_days), observation time (T_hat), and infection rate (I_tend).
Having extracted these data from various papers, the infection constant (k_inf) was calculated, expressed as the average number of individuals in a population of 1000 who are infected in one year.

Vaccine	Participants (N)	T_{day} (days)	$\hat{T}$ (person-years)	$I_{t_{end}}$	k_{inf}
Astra Zeneca	17662	64.80	3135.61	73	23.28
Moderna	14134	83.96	3251.14	11	3.30
BioNTech	18198	43.31	2214	8	3.61

Table 1: Treated arm, values extracted from publications on Covid-19 vaccine clinical trials.

Vaccine	Participants (N)	T_{day} (days)	$\hat{T}$ (person-years)	$I_{t_{end}}$	k_{inf}
Astra Zeneca	8550	64.90	1520.26	130	85.51
Moderna	14073	84.92	3274.34	185	56.50
BioNTech	18325	43.17	2222	162	72.91

Table 2: Placebo arm, values extracted from publications on Covid-19 vaccine clinical trials.

Inverse sampling:

The number of infections in clinical trials was assumed to follow a binomial distribution. The probability of infection was calculated based on the observation time and incidence rate.
The incidence rate was sampled using the inverse transform sampling method. The cumulative density function (CDF) of the incidence rate was derived, and the inverse transform sampling technique was used to generate samples from this distribution.

CDF equation of incidence rate:

$$F(r_{\text{inf}}) = \frac{\int_0^{r_{\text{inf}}} x^n (N - T_{\text{total}} \cdot x)^{N-n}\, dx}{\int_0^{N/T_{\text{total}}} x^n (N - T_{\text{total}} \cdot x)^{N-n}\, dx}$$

Simulations were run 100 times for placebo arms to generate incidence rate distributions.
Infected individuals in vaccine groups were simulated and compared to trial-reported values.
Vaccine efficacy was computed using the formula:

$$\varphi = 1 - \frac{k_{\text{inf}}(\text{vacc.})}{k_{\text{inf}}(\varnothing)}$$

The standard deviation and 95% confidence intervals were computed for the number of infections and vaccine efficacy.
The probability distribution of vaccine efficacy was estimated by stimulating different efficacy values and calculated the conditional probability of observing a given number of infections.

Results

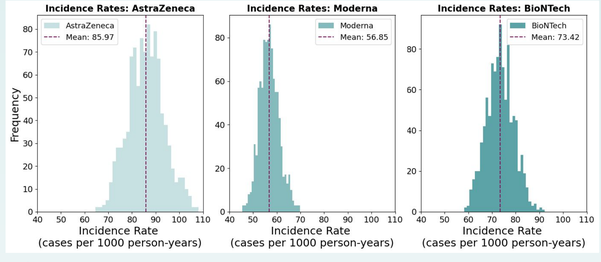

Figure 1: *Histograms of simulated incidence rates for placebo arms of AstraZeneca, Moderna, and BioNTech vaccine trials.*

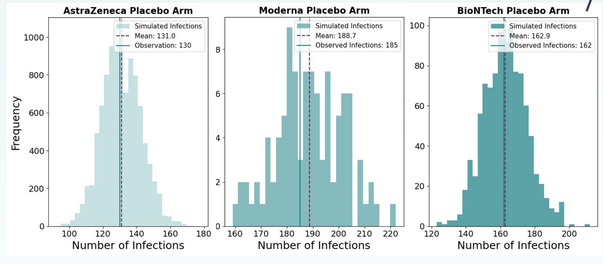

Figure 2: *Histogram of the number of infected individuals at the end of our simulation. The reported numbers from the clinical trial are marked in the same plot.*

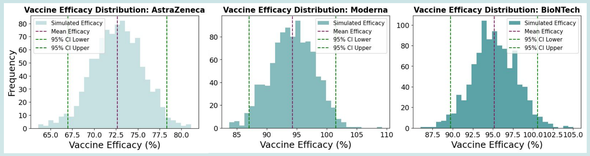

Figure 3: *Simulate vaccine efficiency with confidence interval*

Vaccine	Efficacy (%)		SD (%)	95% CI (%)	
	Calculated	Simulated Mean		Lower Bound	Upper Bound
AstraZeneca	72.82	72.84	2.65	67.65	78.03
Moderna	94.16	94.03	3.74	86.69	101.37
BioNTech	95.04	95.05	2.67	89.82	100.28

Table 3: Comparison of calculated and simulated vaccine efficacy, including standard deviation and 95% confidence intervals.

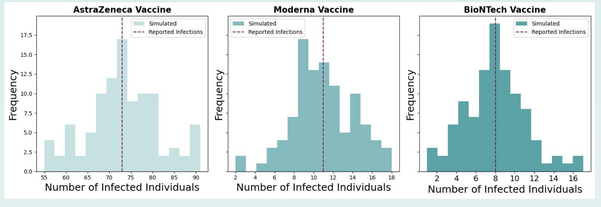

Figure 4: *Histogram of the number of infected individuals at the end of simulation*

Vaccine	Mean Simulated	SD
AstraZeneca	131.03	11.08
Moderna	185.63	14.32
BioNTech	162.31	13.02

Table 4: Comparison of calculated and simulated vaccine efficacy, including standard deviation and 95% confidence intervals.

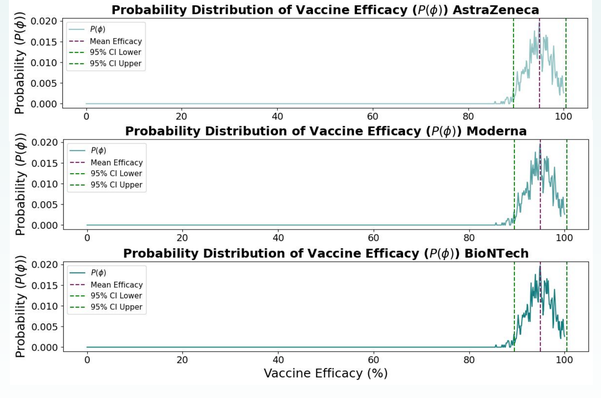

Figure 5: *Simulated vaccine efficacy for AstraZeneca, Moderna, and BioNTech clinical trials*

Conclusion

The clinical trial outcomes for the AstraZeneca, Moderna and BioNTech vaccines are replicated successfully by the stochastic simulation framework. The robustness of our approach is validated by the simulated vaccine efficacy we get, which are closely aligned to the reported values, respectively.

Moderna and BioNTech are highly reliable vaccines because they showed high efficacy(>90%) with minimal uncertainty.

The slightly lower efficacy is demonstrated by AstraZeneca (~73%) with wider uncertainty, reflecting variability in trial conditions.
The 95% confidence intervals and probability distributions provides a proper measure of uncertainty and highlighting the reliability of the efficacy estimates.

These results explain the importance of stochastic simulation in understanding vaccine efficacy and its variability, providing valuable insights for public health decision-making.

References

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