



Estimating the Public Health Impact of MERS-CoV Vaccination in Thailand: A Simulation-based Approach

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Abstract

Objectives: Middle East Respiratory Syndrome coronavirus (MERS-CoV) remains a public health concern for Thailand, because of the risk of importation from Thai pilgrims attending the Hajj. With MERS-CoV vaccines under development, evidence on their potential impact is needed for vaccination planning. This study aimed to estimate the potential public health impact of MERS-CoV vaccination among Thai pilgrims attending the Hajj under different vaccine effectiveness (VE) and transmission scenarios.

Methods: A compartmental model simulated MERS-CoV transmission among Thai and non-Thai pilgrims attending the Hajj over 30 days. Vaccination was applied only to Thai pilgrims before travel. VE scenarios of 30%, 50%, 70%, and 90% were compared with no vaccination across basic reproduction number (R_0) values of 1, 2, 4, 6, and 8. Outcomes included infection burden and transmission dynamics, severe cases, deaths, and timing of case occurrence.

Results: Increasing VE reduced the projected number of infections, severe cases, and deaths across all transmission scenarios. Without vaccination, cumulative infections among Thai pilgrims increased from 0.35 cases at $R_0=1$ to 60.69 cases at $R_0=8$. At $R_0=8$, cumulative incident cases over the 30-day simulation period decreased from 60.69 without vaccination to 6.05 with 90% VE. During the 30-day simulation, the maximum observed daily incidence decreased from 10.15 to 1.01 cases, and the maximum observed prevalence decreased from 33.65 to 3.36 cases. Cumulative severe cases decreased from 15.43 to 1.54 and deaths from 5.66 to 0.57. Vaccination also delayed prevalent cases reaching ≥ 1 case—the threshold for prompt notification—from day 10 to day 23.

Public Health Recommendations: Under lower-transmission conditions, routine vaccination of all Thai pilgrims may not be necessary. However, if MERS-CoV transmission or outbreak activity increases in Saudi Arabia, targeted vaccination should be considered if a safe and effective vaccine becomes available. Further studies should evaluate cost-effectiveness and the combined effects of vaccination and non-pharmaceutical interventions.

Keywords: Middle East respiratory syndrome coronavirus, MERS-CoV, Hajj pilgrims, vaccine effectiveness, model, Thailand

Introduction

Middle East Respiratory Syndrome coronavirus (MERS-CoV) is a zoonotic pathogen first identified in

Saudi Arabia in 2012.^{1–3} Dromedary camels serve as the primary animal reservoir for the virus.^{3,4} Notably, infected dromedaries typically do not manifest clinical illness, which makes animal-level detection reliant on



laboratory testing.^{3–5} Human infection occurs through direct or indirect contact with infected camels, while onward human-to-human transmission has been documented primarily in healthcare and household settings.³ Since its emergence, the World Health Organization has been notified of more than 2,600 laboratory-confirmed human cases from 27 countries, with approximately 84% of these cases reported from Saudi Arabia.^{3,6} The case-fatality rate among reported cases has been approximately 37%.^{3,6} Currently, no licensed vaccines or specific antiviral treatments exist for prevention or treatment, making outbreak control dependent on early detection, patient isolation, and stringent infection prevention measures.

The Hajj pilgrimage represents a public health challenge as one of the world's largest annual mass gatherings, attracting millions of pilgrims to Saudi Arabia.^{7,8} The crowded conditions and close interpersonal contact during the pilgrimage rituals may increase the risk of respiratory infectious disease transmission, including MERS-CoV.

Thailand has reported three confirmed MERS-CoV cases, all of which were imported from the Middle East, with no evidence of local transmission.⁹ However, approximately 13,000 Thai Muslims travel to Saudi Arabia annually for the Hajj pilgrimage, creating a recurring risk of MERS-CoV importation.^{10,11}

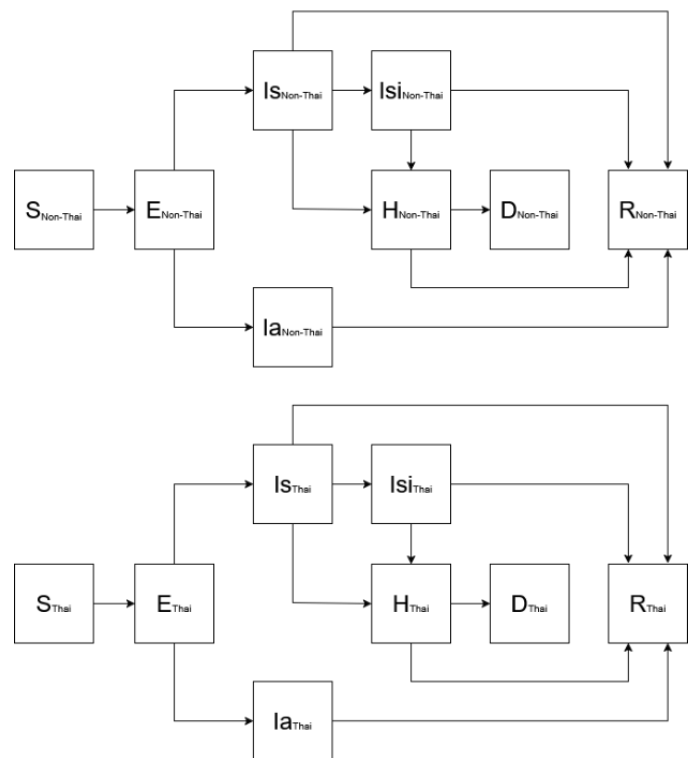
Several MERS-CoV vaccine candidates are currently under clinical development.^{12–14} As effective vaccines become available, countries at risk of importation will need evidence to guide vaccination strategies for specific populations. Although the Hajj rituals last only 5–6 days, most international pilgrims remain in Saudi Arabia for approximately 2–7 weeks, including travel and related activities.^{15,16} Therefore, this study aimed to estimate the potential public health impact of hypothetical MERS-CoV vaccination among Thai Hajj pilgrims under different vaccine effectiveness (VE) and transmission scenarios over a 30-day period, representing the Hajj-related exposure period. Although longer-term disease progression and secondary transmission after pilgrims returned to Thailand were not simulated, estimating infections acquired during this period provides important information for vaccination policy and preparedness planning because it enables health authorities to anticipate healthcare needs and allocate resources for surveillance, laboratory testing, infection prevention and control, and Thai medical teams providing healthcare for Thai Hajj pilgrims in Saudi Arabia.

Methods

Model Framework

A deterministic compartmental continuous-time Susceptible–Exposed–Infectious–Recovered (SEIR) model was constructed to simulate MERS-CoV transmission among pilgrims attending the Hajj over a 30-day period. The simulation covered a 30-day period, representing the approximate duration of Hajj-related potential exposure among pilgrims.

The modelled population comprised 13,000 Thai pilgrims and 1,660,230 non-Thai pilgrims, reflecting the 2025 Hajj quota data.^{11,17} Each group was divided into eight compartments: Susceptible (S), Exposed (E), Symptomatic infectious pre-isolation (Is), Symptomatic infectious post-isolation (Isi), Asymptomatic infectious (Ia), Hospitalized (H), Recovered (R), and Deceased (D) (Figure 1).



The model comprised two interacting populations (Thai and non-Thai pilgrims), each divided into susceptible (S), exposed (E), symptomatic infectious before isolation (Is), symptomatic infectious after isolation (Isi), asymptomatic infectious (Ia), hospitalized (H), deceased (D), and recovered (R) compartments. Transmission occurred within and between the two populations. Vaccination was applied only to Thai pilgrims by reducing susceptibility to infection. Model equations and parameter definitions are provided in Supplementary Tables 1–3.

Figure 1. Structure of the compartmental model used to simulate MERS-CoV transmission among Thai and non-Thai pilgrims attending the Hajj.

Model Assumptions and Parameters

Key epidemiological parameters were derived from published literature and study assumptions (Supplementary Tables 1–2).^{11,17–25}

The total population N is defined as $N = S + E + I_s + I_a + I_{si} + H + R + D$. To account for transmission uncertainty, the basic reproductive number (R_0) was varied across five values (1, 2, 4, 6, and 8). This range reflects the spectrum from low community transmission in Saudi Arabia ($R_0 \approx 0.45$) to extreme superspreading events comparable to the 2015 South Korea nosocomial outbreak ($R_0 \approx 8.1$).^{19–22}

Vaccination was modelled as a reduction in susceptibility to infection, applied exclusively to the Thai pilgrim cohort with full (100%) coverage assumed prior to departure. VE was evaluated at four levels (30%, 50%, 70%, and 90%) against an unvaccinated baseline. The model assumed homogeneous mixing of contacts with symptomatic and asymptomatic infectees, no waning of immunity within the simulation period, zoonotic transmission excluded (human-to-human only), and a closed population. To initiate transmission, non-Thai pilgrims were seeded with 83 initial cases (48 symptomatic and 35 asymptomatic infectious individuals). This seeding represents an assumed rare disease prevalence of one case per 2,000 persons among 166,654 Saudi Arabian pilgrims.¹⁸

Data Analysis

The model was implemented in Vensim Personal Learning Edition; graphical outputs were generated using Microsoft Excel 2016.²⁶ The model equations are presented in Supplementary Table 3.

Incident cases were defined as individuals transitioning from the exposed compartments to an infectious stage (I_a or I_s), while prevalence was defined as the total number of individuals in infectious compartments at any given time. Primary outcomes among Thai pilgrims included cumulative incident cases, 30-day incidence proportion per 100,000 pilgrims, maximum observed daily incidence and prevalence, cumulative incident severe cases, cumulative deaths, and the timing of case occurrence. The day on which cases first reached ≥ 1 case was used as an operational threshold for comparing the timing of case occurrence across scenarios. In practice, a confirmed MERS-CoV case would trigger public health investigation and response in Thailand.²⁷

To account for infections acquired during the 30-day exposure period that had not yet progressed to the infectious stage, total infections acquired by day 30 were calculated as the cumulative number of incident infections plus the number of individuals remaining in the exposed compartment on day 30. The cumulative incidence proportion of total infections was calculated by dividing the total infections acquired by the Thai pilgrim population (13,000) and multiplying by 100,000. Total projected severe cases and deaths were estimated by applying the corresponding transition probabilities described in Supplementary Tables 2. These estimates represent the potential downstream burden arising from infections acquired during the 30-day period and were derived using transition probabilities rather than dynamic simulation beyond day 30.

Results

The projected MERS-CoV infection burden among Thai pilgrims increased as R_0 rose, while the implementation of vaccination consistently mitigated these outcomes across all evaluated scenarios.

In the absence of a vaccine, the cumulative incident cases by day 30 ranged from 0.35 cases under low transmission ($R_0=1$) to 60.69 cases in a high transmission superspreading scenario ($R_0=8$). At $R_0=8$, 90% VE reduced cumulative incident cases from 60.69 to 6.05 cases (Table 1 and Figure 2).

Vaccination flattened the trajectory of the outbreak by reducing both the intensity and peak of transmission. At $R_0=8$, 90% VE reduced the maximum observed daily incidence from 10.15 to 1.01 cases/day and the maximum observed prevalence from 33.65 to 3.36 cases. For most scenarios with $R_0 \geq 2$, the maximum observed incidence and prevalence occurred on day 30, which indicated that transmission was still increasing and that the true epidemic peaks were not reached within the 30-day simulation period (Table 1).

Increasing VE delayed the occurrence of cases. Without vaccination and under high transmission ($R_0=8$), the first case occurred on day 8, whereas a 90% effective vaccine delayed this threshold until day 20. When measured by prevalent cases, the threshold was delayed from day 10 to day 23 (Table 1).

Vaccination reduced severe cases and deaths, particularly under high-transmission scenarios. At $R_0=8$, 90% VE reduced cumulative incident severe cases by day 30 from 15.43 to 1.54 and cumulative deaths from 5.66 to 0.57 compared with no vaccination (Table 1 and Figures 3–4).

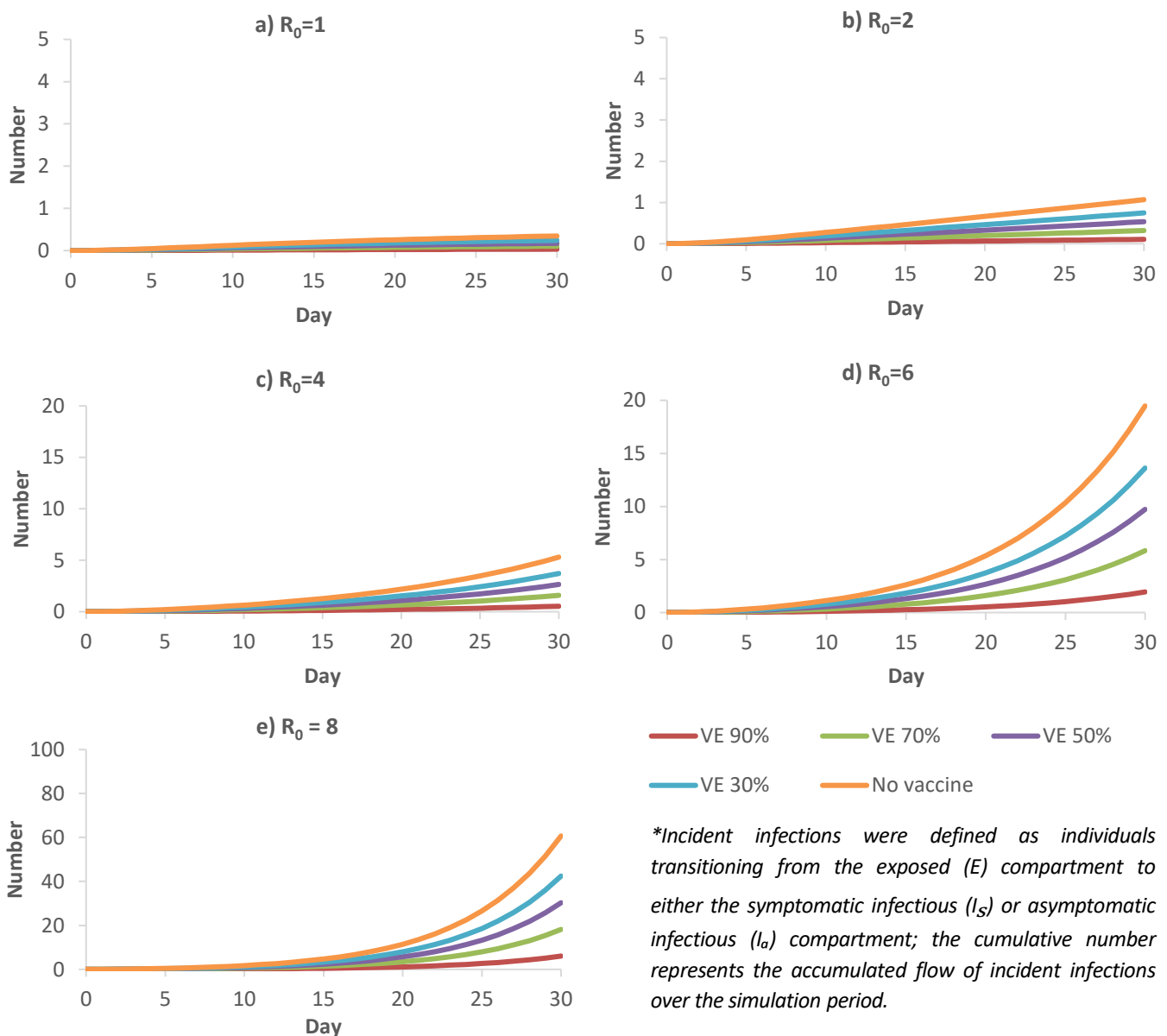
Table 1. Simulation results under different vaccination scenarios according to the basic reproductive number (R_0) over a 30-day simulation period.

Outcome	Details	Scenario	$R_0=1$	$R_0=2$	$R_0=4$	$R_0=6$	$R_0=8$
Infected cases	Cumulative number of incident infections by day 30*	Baseline–no vaccine	0.35	1.07	5.30	19.47	60.69
		VE 30%	0.24	0.75	3.71	13.62	42.45
		VE 50%	0.17	0.53	2.65	9.72	30.31
		VE 70%	0.10	0.32	1.59	5.83	18.17
		VE 90%	0.03	0.11	0.53	1.94	6.05
	30-day incidence proportion (per 100,000 Thai pilgrims) [†]	Baseline–no vaccine	2.66	8.23	40.80	149.77	466.85
		VE 30%	1.86	5.76	28.54	104.77	326.54
		VE 50%	1.33	4.11	20.38	74.80	233.12
		VE 70%	0.80	2.47	12.22	44.86	139.80
		VE 90%	0.27	0.82	4.07	14.94	46.58
	Maximum observed daily incidence (cases/day) [‡]	Baseline–no vaccine	0.02	0.04	0.44	2.47	10.15
		VE 30%	0.01	0.03	0.31	1.72	7.10
		VE 50%	0.01	0.02	0.22	1.23	5.07
		VE 70%	0.00	0.01	0.13	0.74	3.04
		VE 90%	0.00	0.00	0.04	0.25	1.01
	Day of maximum observed daily incidence [‡]	Baseline–no vaccine	7	30	30	30	30
		VE 30%	7	30	30	30	30
		VE 50%	7	30	30	30	30
		VE 70%	7	30	30	30	30
		VE 90%	7	30	30	30	30
	Day on which cumulative incident cases first reached ≥ 1 case [§]	Baseline–no vaccine	NA	29	14	10	8
		VE 30%	NA	NA	16	12	10
		VE 50%	NA	NA	20	14	11
		VE 70%	NA	NA	25	17	14
		VE 90%	NA	NA	NA	25	20
	Maximum observed prevalence (cases/day) [¶]	Baseline–no vaccine	0.09	0.30	2.12	9.55	33.65
		VE 30%	0.06	0.21	1.48	6.68	23.53
		VE 50%	0.05	0.15	1.06	4.77	16.80
		VE 70%	0.03	0.09	0.64	2.86	10.08
		VE 90%	0.01	0.03	0.21	0.95	3.36
	Day of maximum observed prevalence [¶]	Baseline–no vaccine	17	30	30	30	30
		VE 30%	17	30	30	30	30
		VE 50%	17	30	30	30	30
		VE 70%	17	30	30	30	30
		VE 90%	17	30	30	30	30
	Day on which prevalence first reached ≥ 1 case [#]	Baseline–no vaccine	NA	NA	20	13	10
		VE 30%	NA	NA	25	15	12
		VE 50%	NA	NA	30	18	13
		VE 70%	NA	NA	NA	22	16
		VE 90%	NA	NA	NA	NA	23
Exposed cases**	Exposed individuals remaining on day 30	Baseline–no vaccine	0.04	0.21	2.19	12.33	50.76
		VE 30%	0.03	0.15	1.53	8.62	35.51
		VE 50%	0.02	0.10	1.09	6.16	25.35
		VE 70%	0.01	0.06	0.66	3.69	15.20
		VE 90%	0.00	0.02	0.22	1.23	5.06
Severe cases	Cumulative number of incident severe cases by day 30	Baseline–no vaccine	0.15	0.43	1.78	5.62	15.43
		VE 30%	0.11	0.30	1.25	3.93	10.79
		VE 50%	0.08	0.21	0.89	2.81	7.71
		VE 70%	0.05	0.13	0.53	1.68	4.62
		VE 90%	0.02	0.04	0.18	0.56	1.54

Table 1. Simulation results under different vaccination scenarios according to the basic reproductive number (R_0) over a 30-day simulation period (cont.).

Outcome	Details	Scenario	$R_0=1$	$R_0=2$	$R_0=4$	$R_0=6$	$R_0=8$
Deaths	Cumulative number of deaths by day 30	Baseline—no vaccine	0.09	0.25	0.87	2.35	5.66
		VE 30%	0.07	0.17	0.61	1.65	3.96
		VE 50%	0.05	0.12	0.44	1.18	2.83
		VE 70%	0.03	0.07	0.26	0.71	1.70
		VE 90%	0.01	0.02	0.09	0.23	0.57

*Incident infectious cases were defined as individuals transitioning from the exposed compartment (E) to either the symptomatic infectious (I_s) or asymptomatic infectious (I_a) compartment. The cumulative number was obtained by accumulating these incident flows over the 30-day simulation period. [†]The 30-day incidence proportion per 100,000 Thai pilgrims was calculated as the cumulative number of incident infectious cases by day 30 divided by the total Thai pilgrim population (13,000) and multiplied by 100,000. [‡]Daily incidence was defined as the number of individuals transitioning from E to I_s or I_a per day. The maximum observed daily incidence was the highest value during the 30-day simulation period. [§]The day on which cumulative infectious cases first reached ≥ 1 case was used as an operational threshold for comparing the timing of case occurrence across scenarios. In practice, a confirmed MERS-CoV case would trigger public health investigation and response in Thailand. [¶]Prevalence of infectious cases was defined as the number of individuals currently in the symptomatic infectious (I_s) and asymptomatic infectious (I_a) compartments at a given time ($I_s + I_a$). The maximum observed prevalence was the highest value during the 30-day simulation period. ^{‡‡}The day on which the prevalence of infectious cases ($I_s + I_a$) first reached ≥ 1 case. ^{***}Exposed individuals were those remaining in the exposed (E) compartment on day 30 and had not yet transitioned to an infectious compartment. VE: vaccine effectiveness. R_0 : basic reproduction number. NA: not reached during the 30-day simulation period.

**Figure 2. Cumulative number of incident infections among Thai pilgrims attending the Hajj under different vaccine effectiveness (VE) and basic reproduction number (R_0) scenarios over the 30-day simulation period.***

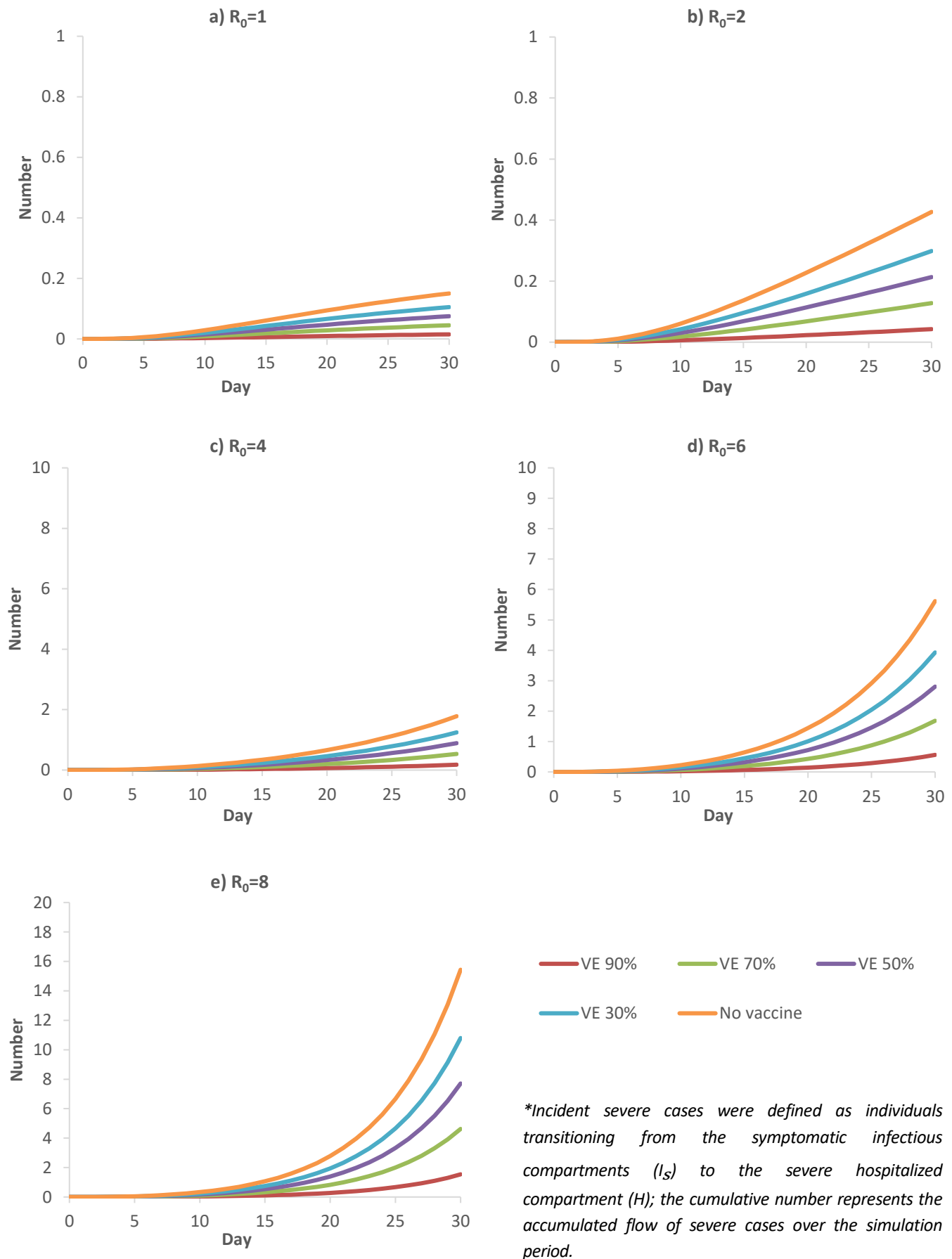


Figure 3. Cumulative number of incident severe cases among Thai pilgrims attending the Hajj under different vaccine effectiveness (VE) and basic reproduction number (R_0) scenarios over the 30-day simulation period.*

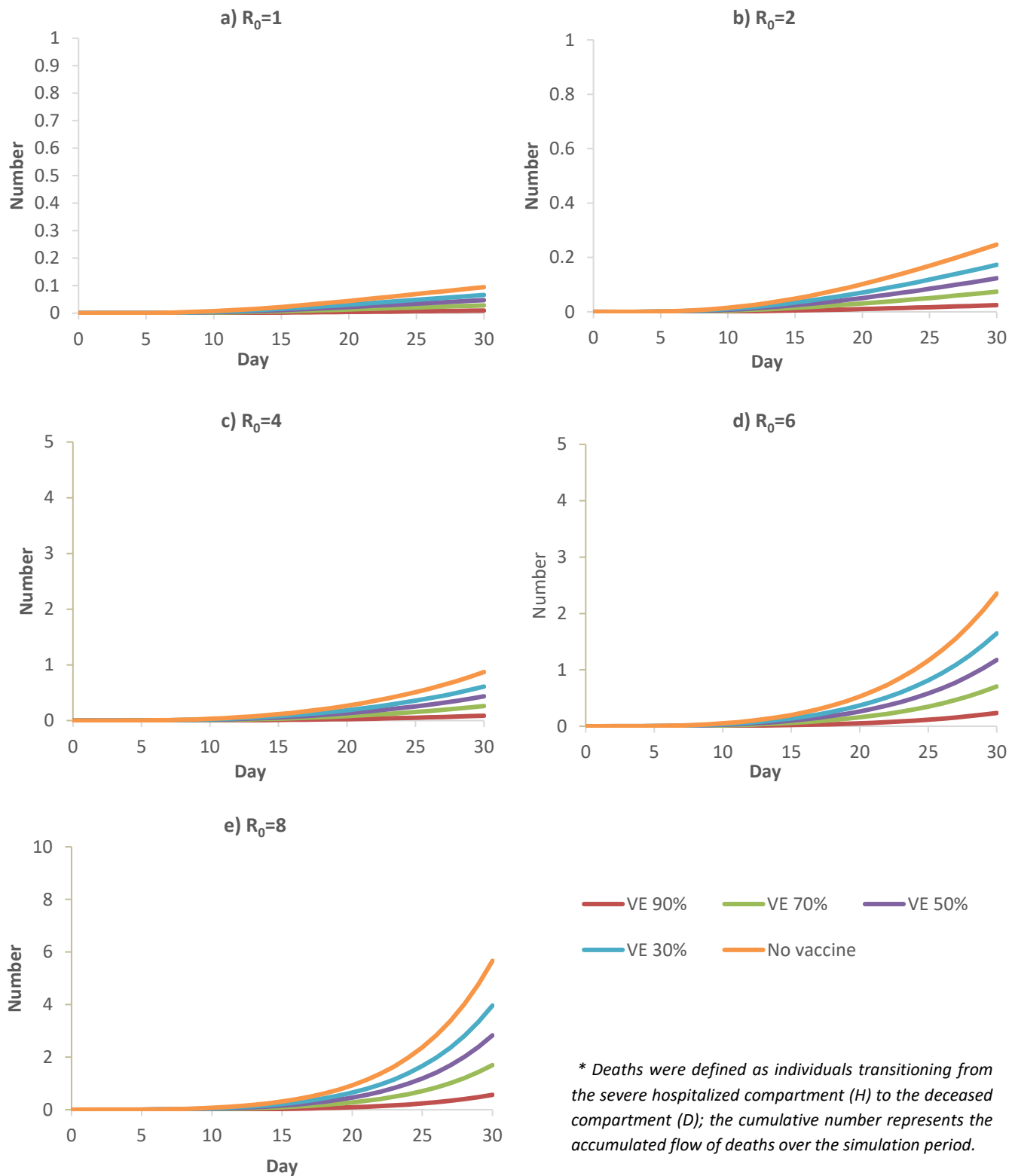


Figure 4. Cumulative number of deaths among Thai pilgrims attending the Hajj under different vaccine effectiveness (VE) and basic reproduction number (R_0) scenarios over the 30-day simulation period.*

Individuals remaining in the exposed compartment at day 30 were included in the total infection burden, because they had already acquired infection, but had not yet progressed to the infectious stage. The total projected disease burden was reduced with increasing VE. At $R_0=8$,

total infections acquired were 111.45 (857.31 per 100,000 Thai pilgrims) without vaccination compared with 11.11 (85.46 per 100,000) with 90% VE. The corresponding total severe cases were 47.19 and 4.70, and total projected deaths were 40.58 and 4.05, respectively (Table 2).

Table 2. Projected total disease burden arising from MERS-CoV infections acquired by Thai pilgrims during the 30-day simulation period under different vaccine effectiveness and basic reproduction number (R_0) scenarios.

Outcome	Scenario	$R_0=1$	$R_0=2$	$R_0=4$	$R_0=6$	$R_0=8$
Total infections acquired*	Baseline–no vaccine	0.39	1.28	7.49	31.80	111.45
	VE 30%	0.27	0.90	5.24	22.24	77.96
	VE 50%	0.19	0.63	3.74	15.88	55.66
	VE 70%	0.11	0.38	2.25	9.52	33.37
	VE 90%	0.03	0.13	0.75	3.17	11.11
Cumulative incidence proportion of total infections acquired (per 100,000 Thai pilgrims)*	Baseline–no vaccine	3.00	9.85	57.62	244.62	857.31
	VE 30%	2.08	6.92	40.31	171.08	599.69
	VE 50%	1.46	4.85	28.77	122.15	428.15
	VE 70%	0.85	2.92	17.31	73.23	256.69
	VE 90%	0.23	1.00	5.77	24.38	85.46
Total severe cases acquired†	Baseline–no vaccine	0.17	0.54	3.17	13.46	47.19
	VE 30%	0.11	0.38	2.22	9.42	33.01
	VE 50%	0.08	0.27	1.58	6.72	23.57
	VE 70%	0.05	0.16	0.95	4.03	14.13
	VE 90%	0.01	0.06	0.32	1.34	4.70
Total deaths acquired‡	Baseline–no vaccine	0.14	0.47	2.73	11.58	40.58
	VE 30%	0.10	0.33	1.91	8.10	28.39
	VE 50%	0.07	0.23	1.36	5.78	20.27
	VE 70%	0.04	0.14	0.82	3.47	12.15
	VE 90%	0.01	0.05	0.27	1.15	4.05

*Total infections acquired by day 30 were calculated as the cumulative number of incident cases plus the number of individuals remaining in the exposed (E) compartment on day 30. Exposed individuals were already infected but had not yet transitioned to an infectious compartment. The 30-day cumulative incidence proportion of total infections acquired was calculated as the total infections acquired by day 30 divided by the total Thai pilgrim population (13,000) and multiplied by 100,000. †Total severe cases were calculated as total infections acquired by day 30 $\times$ 0.58 symptomatic probability $\times$ 0.73 probability of severe disease among symptomatic cases. ‡Total deaths were calculated as total infections acquired by day 30 $\times$ 0.58 $\times$ 0.73 $\times$ 0.86 probability of death among severe cases.

Discussion

This study demonstrated that increasing vaccine effectiveness would consistently reduce the projected MERS-CoV burden among Thai pilgrims across all transmission scenarios. Higher VE levels would yield greater relative reductions in incident cases, severe clinical outcomes, and deaths, particularly as R_0 increased. Beyond reducing the absolute number of infections, vaccination would serve to mitigate the intensity of transmission and suppress the epidemic trajectory by lowering peak daily incidence and prevalence.

The wide R_0 range explored (1–8) reflected variations in MERS-CoV transmissibility across epidemiological settings. Previous studies have generally estimated R_0 below one in community settings in Saudi Arabia, and surveillance among Hajj pilgrims has found little evidence of MERS-CoV circulation.^{11–13,17} In contrast, substantially higher transmission has occurred during healthcare-associated superspreading events, including

the 2015 South Korea nosocomial outbreak ($R_0=8.1$).^{19–22} Therefore, the higher R_0 scenarios in this study represented worst-case rather than routine Hajj conditions.

Vaccination reduced the maximum observed daily incidence and prevalence and delayed case occurrence. At $R_0=8$, 90% VE delayed cumulative incident cases reaching ≥ 1 case by 12 days. Such a delay during a time-limited mass gathering could provide additional time for detection, investigation, isolation, and other control measures. Similar effects have been reported in influenza modelling studies, in which vaccination reduced epidemic burden and influenced the magnitude and timing of epidemic peaks.^{28,29} However, maximum incidence and prevalence frequently occurred on day 30, which indicated that the true epidemic peaks were not reached within the simulation period.

The presence of exposed individuals at day 30 indicated that some pilgrims had acquired infection, but had not yet progressed to the infectious stage.

These individuals could become infectious after returning to Thailand, which highlights the importance of post-travel surveillance, early detection, and rapid isolation. This finding also supports Thailand's current strategy of 14-day post-travel health monitoring and screening of returning pilgrims at airports.³⁰

Nevertheless, these findings should be interpreted in the context of the relatively low incidence of MERS-CoV among Hajj pilgrims. Thailand has previously reported imported MERS-CoV cases, but has not identified local transmission.⁹ Furthermore, Thai pilgrims usually remain in Saudi Arabia for a relatively limited period during the Hajj season. Therefore, routine large-scale vaccination of all Thai pilgrims may not currently be necessary. However, targeted vaccination strategies may be considered during periods with increased numbers of reported MERS-CoV cases, healthcare-associated outbreaks, or superspreading events in Saudi Arabia.

Limitations

This study has several limitations. First, the homogeneous mixing assumption may not reflect structured contact patterns at the Hajj, where interactions depend on accommodation, group composition, and ritual activities. Second, several parameters were based on assumptions or published literature, because of limited epidemiological data specific to MERS-CoV transmission during the Hajj. The lack of evidence-based parameter estimates is likely attributable to the absence of MERS-CoV outbreaks or local transmission in Thailand. Consequently, data on parameter probability distributions are limited, which has restricted the ability to conduct fully stochastic simulations and comprehensive uncertainty analyses. Third, the model assumed that all severe cases were detected and hospitalized. Fourth, vaccination was assumed to reduce susceptibility to infection only, while potential effects on disease severity and mortality were not separately evaluated. Fifth, the model focused solely on human-to-human transmission and did not incorporate zoonotic transmission from camels. In addition, the model focused specifically on Hajj-related travel; therefore, the findings may not be directly generalizable to Umrah, which may involve different travel frequency, duration, and exposure patterns. Finally, the simulation was limited to a 30-day period representing Hajj-related exposure. Although the potential downstream severe cases and deaths arising from infections acquired during this period were estimated, these estimates were based on assumed

transition probabilities rather than explicit simulation beyond day 30. Furthermore, the model did not account for secondary transmission that could occur after infected pilgrims returned to Thailand. Therefore, the longer-term public health impact of vaccination may be underestimated.

Public Health Recommendations

Although the projected burden of MERS-CoV infection among Thai pilgrims was relatively low under lower-transmission scenarios, the model demonstrated that infections, severe cases, and deaths increased rapidly under high R_0 conditions. Therefore, Thailand should continue strengthening preparedness measures for MERS-CoV among pilgrims traveling to Saudi Arabia, particularly during periods with increased numbers of reported MERS-CoV cases, healthcare-associated outbreaks, or superspreading events in Saudi Arabia. Based on the current epidemiological situation, routine large-scale vaccination of all Thai pilgrims might not currently be necessary. However, if MERS-CoV transmissibility, prevalence, or outbreak activity increases in Saudi Arabia, targeted vaccination strategies for high-risk pilgrims should be considered if a safe and effective MERS-CoV vaccine becomes available in the future. Further studies should evaluate the cost-effectiveness of MERS-CoV vaccination strategies and assess the combined effects of vaccination and non-pharmaceutical interventions, including screening, rapid isolation, and post-travel surveillance.

Conclusion

Increasing vaccine effectiveness reduced the projected MERS-CoV burden among Thai Hajj pilgrims, particularly under higher-transmission scenarios, and delayed the occurrence of cases. Although the expected risk remains low under routine transmission conditions, vaccination may provide greater benefit during periods of increased MERS-CoV activity. Infections acquired near the end of travel may become infectious after pilgrims have returned to Thailand, emphasizing the continued importance of post-travel surveillance, early detection, and rapid response. Targeted vaccination may therefore be considered when transmission risk increases, while further studies should assess cost-effectiveness and the combined effects of vaccination and other preventive measures.

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Author Contributions

Natthaprang Nittayasoot: Conceptualization, formal analysis, investigation, methodology, visualization, writing—original draft. **Panithee Thammawijaya:** Conceptualization, methodology, supervision, writing—review & editing. **Rapeepong Suphanchaimat:** Conceptualization, methodology, supervision, writing—review & editing.

Ethical Approval

This study was reviewed and granted exemption from ethical review by the Ethics Committee of the Institute for the Development of Human Research Protections (IHRP), Thailand (COE No. IHRP2026003; IHRP No. 96-2569; exemption date: 19 May 2026).

Informed Consent

Not applicable. This study did not involve human participants, personal data, or identifiable information.

Data Availability

All data used in this study were obtained from publicly available sources and published literature. Model parameters, assumptions, and simulation outputs are described within the manuscript and supplementary materials.

Conflicts of Interest

The authors declare no competing interests.

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This study received no grant from any funding agency.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used generative artificial intelligence tools to assist in language editing and improving clarity of the text. The authors reviewed and edited the content as necessary and took full responsibility for the final content of the manuscript.

References

1. Zaki AM, van Boheemen S, Bestebroer TM, Osterhaus ADME, Fouchier RAM. Isolation of a novel coronavirus from a man with pneumonia in Saudi Arabia. *N Engl J Med*. 2012;367(19):1814–20. doi:10.1056/NEJMoa1211721.
2. Milne-Price S, Miazgowiec KL, Munster VJ. The emergence of the Middle East respiratory syndrome coronavirus. *Pathog Dis*. 2014;71(2):121–36. doi:10.1111/2049-632X.12166.
3. World Health Organization. Middle East respiratory syndrome coronavirus (MERS-CoV) [Internet]. Geneva: World Health Organization; 2025 Dec 11 [cited 2026 Jul 31]. <[https://www.who.int/news-room/fact-sheets/detail/middle-east-respiratory-syndrome-coronavirus-\(mers-cov\)](https://www.who.int/news-room/fact-sheets/detail/middle-east-respiratory-syndrome-coronavirus-(mers-cov))>
4. Alagaili AN, Briesse T, Mishra N, Kapoor V, Sameroff SC, de Wit E, et al. Middle East respiratory syndrome coronavirus infection in dromedary camels in Saudi Arabia. *mBio*. 2014;5(2):e00884-14. doi:10.1128/mBio.00884-14.
5. van den Brand JMA, Wohlsein P, Stalin Raj V, Smits SL, Schippers D, Segales J, et al. Mers coronavirus infection in dromedary camels. *J Comp Pathol*. 2016;154(1):64. doi:10.1016/j.jcpa.2015.10.018.
6. World Health Organization Regional Office for the Eastern Mediterranean. MERS situation update: April 2026 [Internet]. Geneva: World Health Organization Regional Office for the Eastern Mediterranean; [cited 2026 May 26]. <<https://iris.who.int/handle/10665/386322>>
7. Baklola M, Terra M, Alshahrani NZ. Lessons from tragedy: a closer look at the factors behind recent Hajj deaths. *Mass Gathering Medicine*. 2024 Dec;2:100007. doi:10.1016/j.mgmed.2024.100007.
8. Niu S, Xu M. Impact of Hajj on Global Health Security. *J Relig Health*. 2019;58(1):289–302. doi:10.1007/S10943-018-0648-5.
9. Wiboonchutikul S, Manosuthi W, Sangsajja C. Zero transmission of Middle East respiratory syndrome: lessons learned from Thailand. *Clin Infect Dis*. 2017;64(Suppl 2):S167–70. doi:10.1093/cid/cix074.
10. Thai PBS World. Thailand to address rising cost of Hajj pilgrimage [Internet]. Bangkok: Thai Public Broadcasting Service; 2024 Jul 8 [cited 2026 May 26]. <<https://world.thaipbs.or.th/detail/thailand-to-address-rising-cost-of-hajj-pilgrimage/447>>
11. NBT World. Thailand enhances healthcare services for Thai pilgrims attending Hajj 2026 [Internet]. Bangkok: National Broadcasting Services of Thailand; 2026 Feb 11 [cited 2026 Jul 31]. <<https://thainews.prd.go.th/nbtworld/news/view/1786471/?bid=1>>
12. Raadsen MP, Dahlke C, Fathi A, Hardtke S, Kluver M, Krahling V, et al. Safety,

- immunogenicity, and optimal dosing of a modified vaccinia Ankara-based vaccine against MERS-CoV in healthy adults: a phase 1b, double-blind, randomised placebo-controlled clinical trial. *Lancet Infect Dis.* 2025;25(2): 231–42. doi:10.1016/S1473-3099(24)00423-7.
13. Folegatti PM, Bittaye M, Flaxman A, Lopez FR, Bellamy D, Kupke A, et al. Safety and immunogenicity of a candidate Middle East respiratory syndrome coronavirus viral-vectored vaccine: a dose-escalation, open-label, non-randomised, uncontrolled, phase 1 trial. *Lancet Infect Dis.* 2020 Jul 1;20(7):816–26. doi:10.1016/S1473-3099(20)30160-2.
 14. Mayer L, Fathi A, Weichel HM, Raadsen MP, Dahlke C, Mykityn A, et al. Two-year persistence of MERS-CoV-specific antibody and T cell responses after MVA-MERS-S vaccination in healthy adults. *Nat Commun.* 2026;17(1):480. doi:10.1038/s41467-025-68248-5.
 15. Parker S, Almayahi ZK. Saudi Arabia: Hajj and Umrah Pilgrimages. 2025 Apr 23. In: Halsey ES, Angelo KM, Barnett ED, Chen LH, Coyle C, Ericsson CD, et al, editors. *CDC Yellow Book, 2026 edition: health information for international travel* [Internet]. Atlanta (GA): Centers for Disease Control and Prevention (US); 2025 Apr 23 [cited 2026 May 28]. <<https://www.ncbi.nlm.nih.gov/books/NBK620907/>>
 16. Thai PBS. Middle East tensions unlikely to affect Hajj pilgrims, expert says [Internet]. Bangkok: Thai Public Broadcasting Service; 2026 Mar 29 [cited 2026 Aug 3]. <<https://www.thaipbs.or.th/news/content/503965>>. Thai.
 17. General Authority for Statistics. GASTAT: total number of pilgrims performing Hajj 1446H (2025) reaches (1,673,230) [Internet]. Riyadh: General Authority for Statistics; 2025 Jun 5 [cited 2026 May 28]. <https://www.stats.gov.sa/en/w/news/49?utm_source=chatgpt.com>
 18. The Lancet Global Health. The landscape for rare diseases in 2024. *Lancet Glob Health.* 2024 Mar;12(3):e341. doi:10.1016/S2214-109X(24)00056-1.
 19. Park JE, Jung S, Kim A. MERS transmission and risk factors: a systematic review. *BMC Public Health.* 2018 May 2;18(1):574. doi:10.1186/S12889-018-5484-8.
 20. Cauchemez S, Fraser C, Van Kerkhove MD, Donnelly CA, Riley S, Rambaut A, et al. Middle East respiratory syndrome coronavirus: Quantification of the extent of the epidemic, surveillance biases, and transmissibility. *Lancet Infect Dis.* 2014 Jan;14(1):50–6. doi:10.1016/S1473-3099(13)70304-9.
 21. Liu J, Xie W, Wang Y, Xiong Y, Chen S, Han J, et al. A comparative overview of COVID-19, MERS and SARS: Review article. *Int J Surg.* 2020;81:1–8. doi:10.1016/J.IJSU.2020.07.032.
 22. Chang HJ. Estimation of basic reproduction number of the Middle East respiratory syndrome coronavirus (MERS-CoV) during the outbreak in South Korea, 2015. *Biomed Eng Online.* 2017 Jun 13;16(1):79. doi:10.1186/S12938-017-0370-7.
 23. Grant R, Malik MR, Elkholy A, Van Kerkhove MD. A review of asymptomatic and subclinical Middle East respiratory syndrome coronavirus iInfections. *Epidemiol Rev.* 2019;41(1):69–81. doi:10.1093/EPIREV/MXZ009.
 24. Centers for Disease Control and Prevention (US). Clinical overview of MERS [Internet]. Atlanta (GA): Centers for Disease Control and Prevention; 2024 [cited 2026 May 28]. <<https://www.cdc.gov/mers/hcp/clinical-overview/index.html>>
 25. Saad M, Omrani AS, Baig K, Bahloul A, Elzein F, Matin MA, et al. Clinical aspects and outcomes of 70 patients with Middle East respiratory syndrome coronavirus infection: a single-center experience in Saudi Arabia. *Int J Infect Dis.* 2014 Dec 1;29:301–6. doi:10.1016/J.IJID.2014.09.003.
 26. Ventana Systems, Inc. Vensim Personal Learning Edition [Internet]. Harvard (MA): Ventana Systems, Inc.; [cited 2026 Sep 5]. <<https://vensim.com/>>
 27. Department of Disease Control, Ministry of Public Health. Communicable Disease Act B.E. 2558 (A.D.2015) [Internet]. Nonthaburi: Department of Disease Control, Ministry of Public Health; 2015 [cited 2026 Jun 3]. <<https://www.ddc.moph.go.th/uploads/publish/1743420250930084254.pdf>>
 28. Alexander ME, Kobes R. Effects of vaccination and population structure on influenza epidemic spread in the presence of two circulating

- strains. BMC Public Health. 2011 Dec;11 (Suppl 1):S8. doi:10.1186/1471-2458-11-S1-S8.
29. Feng Z, Towers S, Yang Y. Modeling the effects of vaccination and treatment on pandemic influenza. AAPS J. 2011;13(3):427–37. doi:10.1208/S12248-011-9284-7.
30. Yala Provincial Health Office. Epidemiological surveillance information: communicable disease surveillance among Hajj pilgrims [Internet]. Yala: Yala Provincial Health Office;

[cited 2026 Jul 31]. <<https://sites.google.com/view/epiyala/%E0%B8%87%E0%B8%B2%E0%B8%99%E0%B9%80%E0%B8%9D%E0%B8%B2%E0%B8%A3%E0%B8%B0%E0%B8%A7%E0%B8%87%E0%B9%82%E0%B8%A3%E0%B8%84%E0%B8%95%E0%B8%94%E0%B8%95%E0%B8%AD%E0%B9%83%E0%B8%99%E0%B8%9C%E0%B8%9B%E0%B8%A3%E0%B8%B0%E0%B8%81%E0%B8%AD%E0%B8%9A%E0%B8%9E%E0%B8%98%E0%B8%AE%E0%B8%88%E0%B8%A2>>. Thai.