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Impact of mitigating obesity, smoking, and physical inactivity on type 2 diabetes mellitus burden in Oman: insights from mathematical modeling

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ABSTRACT

Introduction To estimate the impact of reducing obesity, smoking, and physical inactivity (PIA) prevalence, and of introducing physical activity (PA) as an explicit intervention, on the prevalence, incidence, and mortality of type 2 diabetes mellitus (T2DM) in Oman.

Research design and methods A deterministic population-level mathematical model was employed to investigate the impact of different scenarios for reducing T2DM risk factors on T2DM epidemiology. The model was stratified by sex, age group, risk factor status, T2DM status, and intervention status and parameterized with nationally representative data. Intervention scenarios were calculated and compared with a baseline (no-intervention) scenario for changes in T2DM prevalence, incidence, and mortality among adult Omanis between 2020 and 2050.

Results In the no-intervention scenario, T2DM prevalence increased from 15.2% in 2020 to 23.8% in 2050. Achieving the goals of halting the rise of obesity, reducing smoking by 30%, and reducing PIA by 10% as outlined in the WHO's Global Action Plan for Non-communicable Diseases (implemented between 2020 and 2030 and then maintained between 2031 and 2050) would reduce T2DM prevalence by 32.2%, cumulative incidence by 31.3%, and related deaths by 19.3% by 2050. Halting the rise of or reducing obesity prevalence by 10%–50% would reduce T2DM prevalence by 33.0%–51.3%, cumulative incidence by 31.9%–53.0%, and related deaths by 19.5%–35.6%. Reducing smoking or PIA prevalence by 10%–50% would lead to smaller reductions of less than 5% in T2DM prevalence, cumulative incidence, and related deaths. Introducing PA with varying intensities at a 25% coverage would reduce T2DM prevalence by 4.9%–14.1%, cumulative incidence by 4.8%–13.8%, and related deaths by 3.4%–9.6% by 2050.

Conclusions Intervention-for-prevention efforts targeting obesity reduction and introducing PA could result in major reductions in the T2DM burden. Prioritizing such interventions could alleviate the burden of T2DM in Oman and other countries with similarly high T2DM and obesity burdens.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Type 2 diabetes mellitus (T2DM) represents a rapidly escalating global health challenge, with a particularly high prevalence in the Middle East and North Africa (MENA) region. Among MENA countries, Oman is confronting a large diabetes burden, evidenced by a T2DM prevalence of 11.8% in 2021. Forecasts indicate a potential doubling of the population living with T2DM within the next three decades in Oman. Efforts to mitigate this epidemic highlight the critical role of addressing modifiable risk factors, as delineated in the World Health Organization's Global Action Plan for the Prevention and Control of Non-communicable Diseases. Nevertheless, a limited number of quantitative studies have assessed country-specific impact of interventions aimed at these risk factors on the epidemiology of T2DM.

WHAT THIS STUDY ADDS

⇒ This study utilized a mathematical modelling approach to assess the impact of various intervention scenarios on the reduction of T2DM prevalence, incidence, and mortality in Oman, by targeting modifiable T2DM-related risk factors. The results demonstrated that addressing obesity, the primary catalyst of the epidemic, could substantially decrease T2DM cases by 2050. For instance, a 50% reduction in obesity prevalence could prevent half of the T2DM cases by 2050. Moreover, interventions that enhance physical activity were effective in lowering T2DM incidence, albeitalthough to a lesser degree than those targeting obesity. This research underscores the importance of population-level interventions in mitigating modifiable risk factors for T2DM, providing insights for Oman and other nations facing similar challenges with T2DM and obesity epidemics.

INTRODUCTION

Type 2 diabetes mellitus (T2DM) remains one of the fastest-growing global health epidemics of the 21st century, constituting approximately 90% of all diabetes cases.[1] The rising prevalence of T2DM is attributed to a complex interplay of non-modifiable risk factors, including age, genetics, and sociodemographics, alongside modifiable risk

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE AND POLICY

⇒ The study provided quantitative evidence to inform the prioritization of public health efforts, resource allocation, and the enhancement of policies, programs, and research aimed at reducing the burden of T2DM in Oman, with implications for other MENA countries and beyond. The approach used in this study can be adapted and applied to other countries, offering insights into the quantitative impact of population-level interventions on risk factors for tackling the T2DM epidemic.

factors, including diet, physical inactivity (PIA), body weight and shape, and substance use.[2–6] The Middle East and North Africa (MENA) region bears one of the highest regional T2DM prevalence globally at 16.2% in 2021.[1] One in six (73 million) adults aged 20–79 years in MENA were living with diabetes, with projections anticipating an 86% increase by 2045, reaching one in five adults (136 million).[1] Further, 20.2% of all deaths (796,000 deaths) were attributed to diabetes in MENA, which has the highest percentage (24.5%) of diabetes-related deaths in people of working age (those under the age of 60).[1]

Oman, situated in the MENA region, grapples with a high diabetes prevalence of 11.8% in 2021.[1] Between 1991 and 2017, several population-based surveys highlighted the rising prevalence of diabetes (11.0% to 15.0%), obesity (13.0% to 35.0%), tobacco use (2.0% to 9.0%), and PIA (38.0% to 42.0%) among Omani nationals aged 20–79 years,[2 7–12] who constitute approximately 58% of the population.[13] A recent modeling study predicted that, if no interventions are implemented, the prevalence of T2DM among Omanis would reach 18.0% in 2030 and 23.8% in 2050.[14] This surge translates into a projected 200% increase in individuals living with T2DM between 2020 and 2050.[14] The burden of T2DM extends to economic implications, where, by 2050, it is expected to account for 29.0% of Oman's national health expenditure, placing an added strain on existing health service financing.[14] Obesity was found to be the primary risk factor driving these alarming T2DM trends.[14]

Public health interventions aimed at reducing the burden of T2DM through targeting its key risk factors are of utmost importance. Implementing such interventions aligns with Oman's Health Vision 2050, a comprehensive "health-in-all policies" plan involving all government sectors in the prevention and control of non-communicable diseases (NCDs).[15] Oman has also committed to diabetes prevention through initiatives such as the Gulf Cooperation Council Action Plan[16] and collaborative efforts outlined in the Joint Statement of the Health Ministers in the Cooperation Council States about Diabetes to leverage political, material, and community support and action.[16] Investing in T2DM reduction strategies aligns with Oman's established commitments and ongoing efforts to combat the diabetes epidemic.

Strategies that focus on reducing and controlling modifiable risk factors to reduce the T2DM burden have demonstrated their effectiveness in reducing the T2DM burden.[17–22] The WHO's Global Action Plan for the Prevention and Control of NCDs highlights voluntary global policy targets to be achieved by 2025 and later extended to 2030,[23] which include a 25% relative reduction in premature mortality resulting from NCDs, halting the rise of diabetes and obesity, and decreasing the prevalence of behavioral risk factors for NCDs such as tobacco use, unhealthy diet, and PIA.[24–26] Yet, only a small number of studies have quantitatively evaluated country-specific effects on T2DM epidemiological trends when intervening on these risk factors.[27–31]

This study employed mathematical modeling to evaluate the impact of various generic "*what-if*" intervention scenarios on reducing T2DM prevalence, incidence, and related deaths by targeting T2DM-related risk factors in Oman between 2020 and 2050. The study also aims to showcase the potential implications of reducing T2DM-related risk factors for countries with high T2DM prevalence such as Oman, where a similar methodology and approach can be applied.

METHODS

Mathematical modeling methodology

A T2DM age-structured and sex-structured mathematical modeling methodology developed by Awad *et al*[14 30] was customized to investigate the impact of various generic "*what-if*" intervention scenarios on T2DM epidemiology of Omanis between 2020 and 2050. This three-decade timeframe was chosen to allow sufficient time for an intervention to be scaled up and its impact to be observed. The model applied specific data from Oman and considered recent efforts to enhance interventions aimed at reducing the prevalence of T2DM risk factors in Oman. The details of the model structure, conceptual framework, equations, assumptions, parameterization, and fitting are available in the publications by Awad *et al*[14 30–32] and are summarized in figure 1. Previous uncertainty analyses were conducted to validate the modeling projections for T2DM in Oman over the coming decades and these revealed overall narrow uncertainty intervals.[14]

In brief, this population-based deterministic compartmental model stratified the population by sex, age, key T2DM-related risk factors and their overlap, and T2DM status (with and without T2DM). Three key risk factors, identified from various surveys in Oman,[7–12 33] were incorporated: obesity, physical inactivity (PIA), and smoking. Obesity was defined as a body mass index (BMI) ≥30 kg/m^2 across all age groups. PIA levels were defined as less than 30 minutes of daily moderate or vigorous exercise, or less than 150 minutes per week of physical activity (PA) levels.[34 35] Smoking was defined as current tobacco use (Yes/No). The population was further stratified based on engagement in PA as an intervention,[36] categorizing every individual

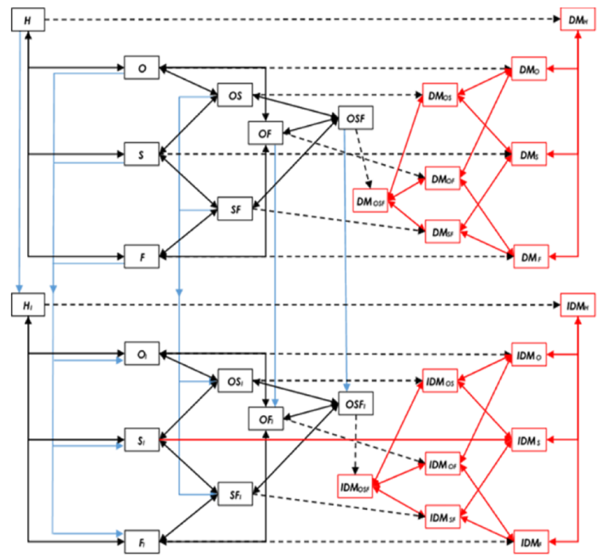
Methodology		Description
Conceptual framework		
Type 2 diabetes mellitus model structure		○ Expressed in terms of a set of 1,280 coupled differential equations. ○ Disaggregated the population into: ○ Sex (female and male) ○ 20 five-year age bands (0–4, 5–9… 95–99 years old) ○ Four main susceptible classes: "healthy" (i.e., non-obese, non-smoker, physically active, and non-diabetic), obese, smoker, and physically inactive ○ Four susceptible classes with overlapping risk factors ○ Eight T2DM status classes based on the risk-factor status ○ Intervention state
Data Sources	Natural history and mortality data	○ Sex- and age-specific relative risks of developing T2DM for key risk factors were obtained from systematic reviews and meta-analyses of prospective cohort studies:(4-6) ○ Relative risk of developing T2DM if obese(6) ○ Relative risk of developing T2DM if current smoker(4) ○ Relative risk of developing T2DM if physically inactive(5) ○ Relative risk of developing T2DM if the individual had more than one risk factor was assumed to be the multiplicative of the individual risks. ○ Relative risk of mortality in T2DM as compared to the general population was obtained from the DECODA study.(67)
	Prevalence data	Epidemiological data were obtained from four national and two regional surveys conducted in Oman.(7-12, 32) Data included sex- and age-specific (by 5-year age band) prevalence for: ○ T2DM ○ Obesity ○ Smoking ○ Physical inactivity
	Demographic data	Demographic data were obtained from the National Centre for Statistics and Information of Oman.(13) Demographic data included: ○ Total and sex-specific population size ○ Age-specific population size and/or distribution
Quality assessment		A survey's quality was assessed and weighted in the model fitting based on: ○ National representativeness of the survey
Fitting method		○ The model was fitted to all available country-specific data using a nonlinear least-square fitting method.(36) ○ Parameters quantified through best fit included sex- and age-specific: ○ T2DM baseline incidence rate (i.e., incidence rate from "healthy" to T2DM) ○ Transition rate from healthy to obese ○ Transition rate from obese to healthy ○ Transition rate from healthy to smoker ○ Transition rate from smoker to healthy ○ Transition rate from healthy to physically inactive ○ Transition rate from physically inactive to healthy

Figure 1 A concise overview of the mathematical modeling methodology employed in this study. Additional information regarding the model can be found in earlier publications that have used this model.[14 30–32] DECODA, Diabetes Epidemiology:Collaborative Analysis Of Diagnostic Criteria in Asia; DMx,Disease based on health state X; IDMx, Disease based on health state X with intervention; F, Physically inactive; F_1, Physically inactive with intervention; H, Health; H_1, Healthy with intervention; O, Obese; O_1, Obese with intervention; OF, Obese and physically inactive; OF_1, Obese and physically inactive with intervention; OS, Obese and smoker; OS_1, Obese and smoker with intervention; OSF, Obese,smoker and physiccally inactive; OSF_1, Obese,smoker, and physically inactive with intervention; S, Smoker; S_1, Smoker with intervention; SF, Smoker and physically inactive; SF_1, Smoker and physically inactive with intervention.

susceptible to T2DM (those without T2DM) according to their participation in PA, distinguishing between those who engaged and those who did not engage in PA as a preventive measure (online supplemental table S1). Similar methods and interventions were applied in a previous study using Qatar as a case study.[30]

Parameterization of the demographics, T2DM natural history, and effects of T2DM-related risk factors was informed by existing evidence (figure 1 and online supplemental table S1) or obtained through model fitting. The model was fitted to sex-specific and age-specific survey data on T2DM, obesity, smoking, and PIA prevalence from Oman,[7–12 14 33] using a non-linear least-square fitting method.[37] Details on the surveys used can be found in online supplemental table S2.[14] The sex-specific and age-specific demographic structure of the Omani population was obtained from the National Centre for Statistics and Information of Oman (online supplemental figure S1).[13] T2DM incidence rates and six other sex-specific and age-specific transition rates were derived through the model's best fit to the input data. The model was coded and analyzed using MATLAB 2019a.[38] The MATLAB codes are available on request from the authors.

Intervention scenarios targeting T2DM-related risk factors

The investigated interventions and their scenarios are summarized in online supplemental table S3. For each modeled scenario, the intervention was initiated in 2020 and scaled up to 2030 among the Omani population. The prevalence of risk factors and coverage of the PA intervention achieved by 2030 were then maintained from 2031 to 2050. The intervention scenarios targeted only the susceptible (no T2DM) population, as the focus is on examining the impact of primary prevention health interventions on the incidence of T2DM, rather than on managing or mitigating health complications associated with T2DM.

The impact of each intervention scenario was measured through changes in the epidemiological outcomes of T2DM prevalence, incidence or cases averted, and related deaths averted among Omanis aged 20–79 years between 2020 and 2050. The predicted T2DM burden measures in the presence of the intervention were compared with those in the baseline scenario with no intervention.[14 30 32] Each modeled scenario is briefly explained below.

Impact of WHO's Global Action Plan for NCDs

Although the WHO's Global Action Plan for NCDs included nine voluntary global targets, such as reductions in alcohol use, sodium intake, and blood pressure, the first modeled scenario investigated only the impact of changing the prevalence of obesity, smoking, and PIA, as these are the modifiable risk factors directly relevant to T2DM prevention.[24] Between 2020 and 2030, the increase in obesity prevalence was halted, while the prevalence of smoking and PIA were linearly reduced by 30% and 10%, respectively, as per targets three and five. By 2030, the prevalence of obesity, smoking, and PIA reached 35.9%, 4.6%, and 31.5%, respectively.

Impact of reducing the prevalence of T2DM-related risk factors

In the three subsequent modeled scenarios, the prevalence of obesity, smoking, and PIA was separately reduced by various proportions. Based on the prevalence in 2020 for each risk factor in the Omani population, a relative reduction in risk factor prevalence of 10%, 20%, 30%, 40%, and 50% by 2030 was assumed. The first set of scenarios reduced the prevalence of obesity from 35.9% in 2020 to 32.3%, 28.7%, 25.1%, 21.5%, and 18.0% by 2030, respectively. The second set of scenarios reduced the prevalence of smoking from 6.6% in 2020 to 5.9%, 5.3%, 4.6%, 4.0%, and 3.3% by 2030, respectively. The third set of scenarios reduced the prevalence of PIA from 35.1% in 2020 to 31.5%, 28.0%, 24.5%, 21.0%, and 17.5%, respectively.

Additional analyses were conducted to assess the impact of reducing obesity prevalence, assuming a 30.0% relative reduction, for both men and women separately as well as by age group.

Impact of introducing different intensities of PA as an intervention

In the last modeled scenario, we assessed the impact of explicitly introducing different intensities of PA as an intervention. This approach differs from the above modeled scenario, which focused on reducing the prevalence of PIA. PA intervention involves actively increasing PA levels, while PIA represents the natural day-to-day state. Consequently, they represent distinct risk or protective factors for T2DM.

Intervening with PA was assumed to reduce the risk of developing T2DM among susceptible (no T2DM) individuals in all intervention groups, that is, healthy, obese, smokers, or PIA. Based on evidence from a systematic review and meta-analysis, five levels of PA were assumed to reduce T2DM risk: vigorous, moderate, low-intensity, leisure time, and walking.[39] The pooled adjusted relative risks (RRs) for these PA interventions, compared with the baseline with no intervention, ranged from 0.61 for vigorous activity to 0.85 for walking.[30 39] The RRs of developing T2DM were included, assuming independence of the effects of the risk factors. The coverage of each of the PA interventions in the population was assumed to reach 25% by 2030. This assumption was based on evidence indicating that intervention strategies that increased access to places for PA, alongside informational outreach activities, may considerably increase the proportion of the population that is physically active.[40]

RESULTS

Baseline scenario of no intervention

In the baseline scenario with no intervention, T2DM prevalence was projected to increase from 15.2% in 2020 to 18.0% in 2030, and 23.8% in 2050. T2DM incidence (number of new cases) was estimated at 17,230, 25,432, and 47,560 in 2020, 2030, and 2050, respectively. The total number of T2DM-related deaths was projected to be 6219, 9203, and 18,300 in 2020, 2030, and 2050, respectively. The prevalence in 2020 of obesity, smoking, and PIA among the Omani population was 35.9%, 6.6%, and 35.1%, respectively.

Impact of WHO's Global Action Plan for NCDs on T2DM burden

The modeled scenario, which aimed to reduce T2DM risk factors to levels recommended by the WHO Global Action

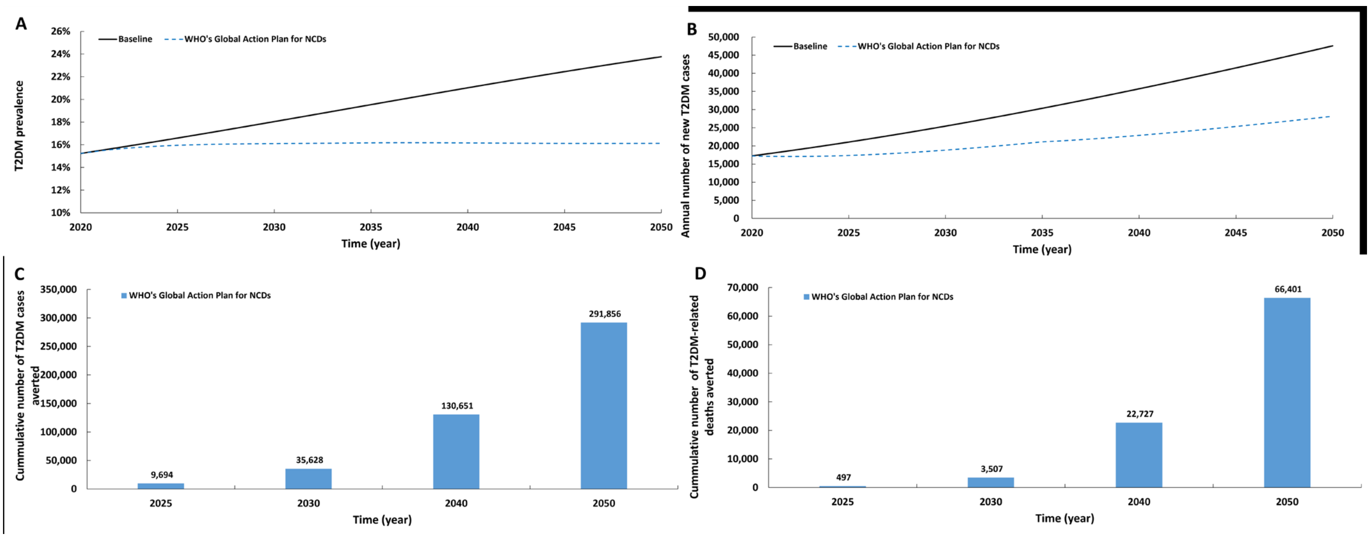


Figure 2 Projected impact of lowering obesity, smoking, and physical inactivity prevalence among Omanis aged 20–79 years in line with the WHO's Global Action Plan for Non-communicable Diseases on (A) T2DM prevalence, (B) annual number of new T2DM cases, (C) cumulative number of T2DM cases averted, and (D) cumulative number of T2DM-related deaths averted. NCDs, Non-communicable Diseases; T2DM, type 2 diabetes mellitus.

Plan for NCDs, has resulted in a meaningful, yet somewhat modest, reduction in the T2DM burden (figure 2). T2DM prevalence was projected to reach 16.1% by 2030 and remain at this level up to 2050, implying a relative reduction of 10.8% and 32.2% in prevalence by 2030 and 2050, respectively, compared with the baseline scenario.

T2DM incidence (annual number of new cases) was estimated at 18,828 and 28,175 in 2030 and 2050, respectively, compared with 25,432 and 47,560 in the baseline scenario for those same years, a reduction of 26.0% and 40.8%, respectively. The number of T2DM cases averted (ie, the cumulative incidence averted) was calculated as 35,628 and 291,856 by 2030 and 2050, respectively, implying reductions of 16.9% and 31.3%, respectively, relative to the baseline scenario. The number of averted T2DM-related deaths was 3507 and 66,401 by 2030 and 2050, respectively, implying reductions of 4.6% and 19.3%, respectively, relative to the baseline scenario.

Impact of reducing obesity prevalence on T2DM burden

The six modeled scenarios for reducing obesity had a substantial impact on alleviating the T2DM burden, with a higher reduction in T2DM burden correlating with greater reductions in obesity. In 2030, across the six modeled scenarios, obesity prevalence decreased from 35.9% in the scenario halting obesity, down to 18.0% in the scenario where obesity was reduced by 50% (figure 3).

In 2030, across these scenarios, T2DM prevalence ranged from 13.4% to 16.1%, implying a relative reduction in the range of 25.6% to 10.6%, respectively,

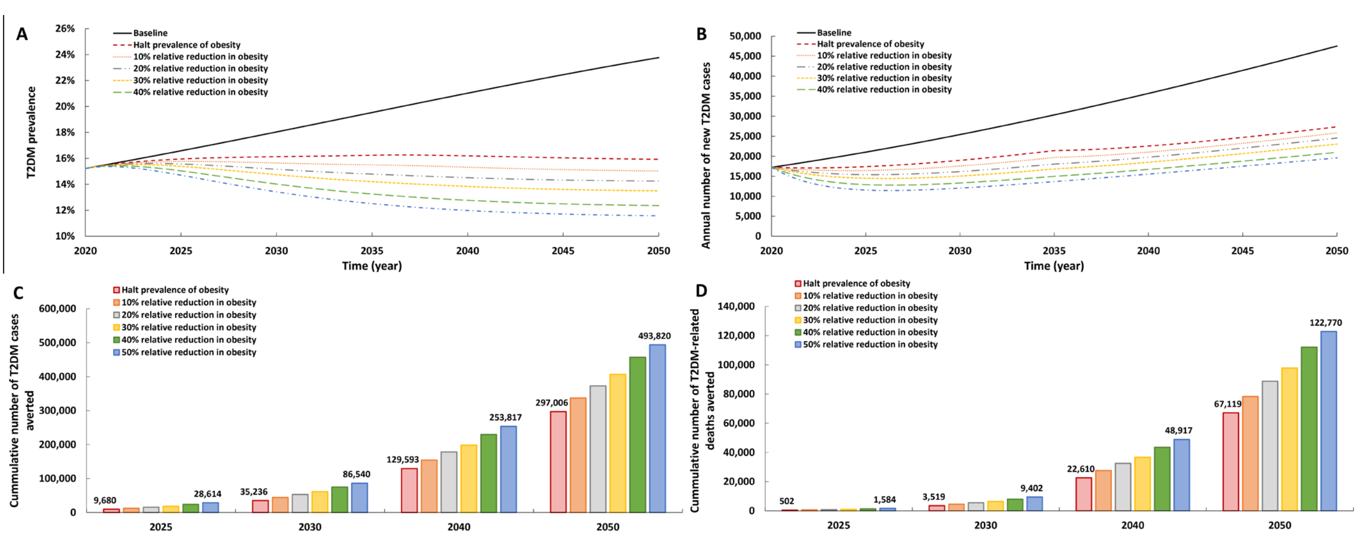


Figure 3 Projected impact of lowering obesity prevalence among Omanis aged 20–79 years on (A) T2DM prevalence, (B) annual number of new T2DM cases, (C) cumulative number of T2DM cases averted, and (D) cumulative number of T2DM-related deaths averted. T2DM, type 2 diabetes mellitus.

compared with the baseline scenario (figure 3). T2DM incidence ranged between 12,036 and 18,964, a reduction in the range of 52.7% to 25.4%, respectively. By 2030, the number of new cases averted ranged between 35,236 and 86,540, a reduction in the range of 16.7% to 40.9%, respectively. The number of averted T2DM-related deaths ranged between 3519 and 9402, a reduction in the range of 4.6% to 12.3%, respectively.

In 2050, across these scenarios, T2DM prevalence ranged from 11.6% to 15.9%, implying a relative reduction in the range of 51.3% to 33.0%, respectively, compared with the baseline scenario (figure 3). T2DM incidence ranged between 19,593 and 27,373, a reduction in the range of 58.8% to 42.4%, respectively. By 2050, the number of new cases averted ranged between 297,006 and 493,820, a reduction in the range of 31.9% to 53.0%, respectively. The number of averted T2DM-related deaths ranged between 67,119 and 122,770, a reduction in the range of 19.5% to 35.6%, respectively.

By targeting a 30% reduction in obesity prevalence separately for women and men, the greatest reduction in T2DM prevalence was achieved by reducing obesity among women. T2DM prevalence in the population was reduced to 17.5% in 2050, implying a relative reduction of 26.2% compared with the baseline scenario (online supplemental figure S2).

By targeting a 30% reduction in obesity prevalence separately for each age group, the greatest reduction in T2DM prevalence was achieved by reducing obesity among younger age groups (25–29, 30–34, and 35–39 year olds). T2DM prevalence in the population was reduced to 18.8%, 18.6%, and 18.9% in 2050, respectively, implying a relative reduction of 20.9%, 21.9%, and 20.5%, respectively, compared with the baseline scenario (online supplemental figure S3).

Impact of reducing smoking or PIA prevalence on T2DM burden

The six modeled scenarios for reducing smoking and PIA had generally a small impact on alleviating the T2DM burden. In 2050, across the six modeled smoking reduction scenarios, T2DM prevalence, incidence, and mortality were reduced by less than 1% compared with the baseline scenario (figure 4).

However, in 2050, across the six modeled PIA reduction scenarios, T2DM prevalence ranged from 22.7% to 23.5%, implying a relative reduction in the range of 4.6% to 1.2%, respectively, compared with the baseline scenario (figure 5). T2DM incidence ranged between 45,663 and 47,005, a reduction in the range of 4.0% to 1.2%, respectively. By 2050, the number of new cases averted ranged between 10,363 and 42,449, a reduction in the range of 1.1% to 4.6%, respectively. The number of averted T2DM-related deaths ranged between 2508 and 10,941, a reduction in the range of 0.7% to 3.2%, respectively.

Impact of intervening with different intensities of PA on T2DM burden

Across the five modeled scenarios of intervening with different intensities of PA, vigorous PA intensity resulted in the highest reduction in T2DM burden, whereas walking resulted in the lowest reduction (figure 6).

In 2050, across these scenarios, T2DM prevalence ranged from 20.4% to 22.6%, implying a relative reduction in the range of 14.1% to 4.9%, respectively, compared with the baseline scenario (figure 6). T2DM incidence ranged between 41,450 and 45,523, a reduction in the range of 12.8% to 4.3%, respectively. By 2050, the number of new cases averted ranged between 44,940 and 128,610, a reduction in the range of 4.8% to 13.8%,

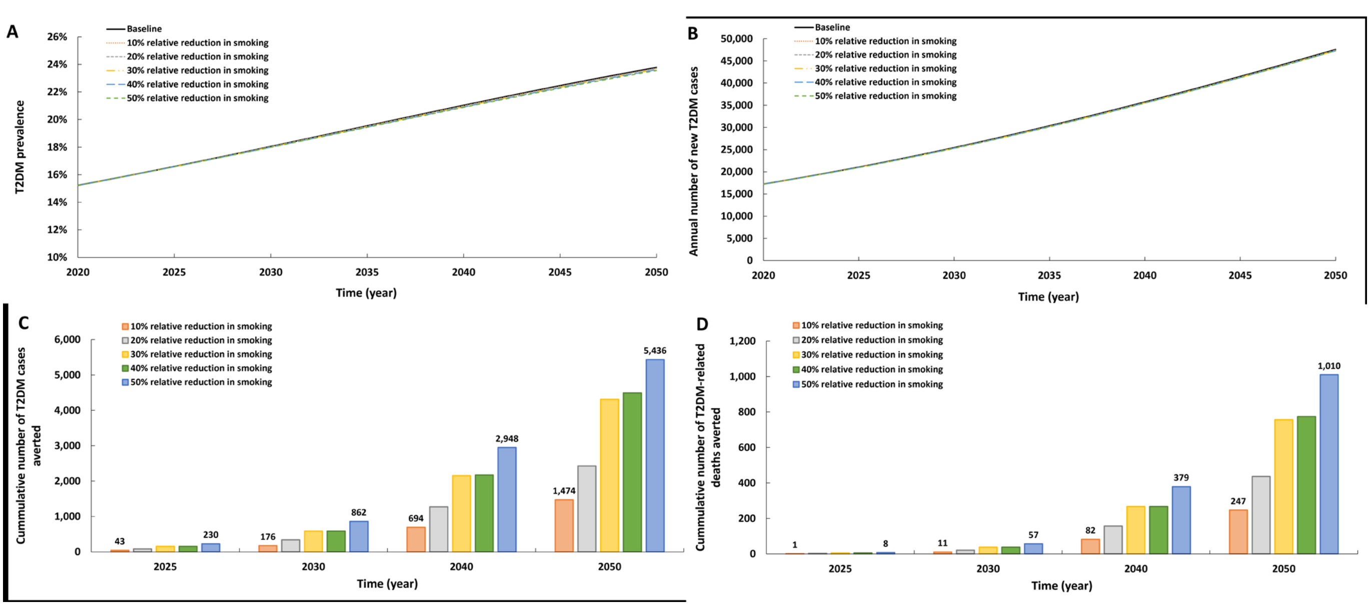


Figure 4 Projected impact of lowering smoking prevalence among Omanis aged 20–79 years on (A) T2DM prevalence, (B) annual number of new T2DM cases, (C) cumulative number of T2DM cases averted, and (D) cumulative number of T2DM-related deaths averted. T2DM, type 2 diabetes mellitus.

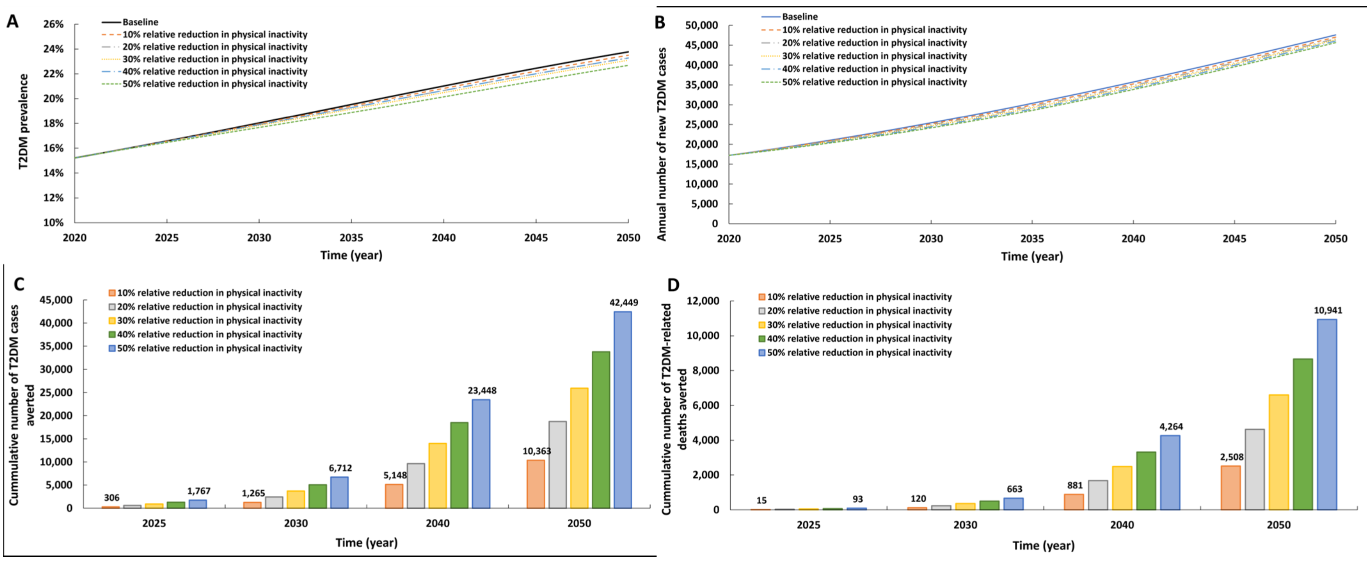


Figure 5 Projected impact of lowering physical inactivity prevalence among Omanis aged 20–79 years on (A) T2DM prevalence, (B) annual number of new T2DM cases, (C) cumulative number of T2DM cases averted, and (D) cumulative number of T2DM-related deaths averted. T2DM, type 2 diabetes mellitus.

respectively. The number of averted T2DM-related deaths ranged between 11,655 and 32,981, a reduction in the range of 3.4% to 9.6%, respectively.

DISCUSSION

This study used mathematical modeling to predict the impact of reducing T2DM risk factors on Oman's large T2DM epidemic. Without interventions, T2DM incidence in this country is projected to increase from 17,230 new cases in 2020 to 47,560 by 2050. Targeting key T2DM risk factors could lead to substantial reductions in T2DM prevalence, incidence, and related deaths. Reducing obesity had the largest impact, but promoting PA also contributed considerably. Implementing the WHO's Global Action Plan for NCDs[24] could lead to meaningful reductions in the T2DM burden, potentially preventing one-third of new cases by 2050. Overall, these findings show similarity to those obtained from similar modeling work applied to Qatar,[30] another country with a high T2DM burden, suggesting that many of the findings may be applicable to other high-burden countries, particularly in the MENA region.

The findings underscore that major reductions in T2DM incidence cannot be achieved without reducing obesity prevalence. This outcome aligns with expectations, considering obesity is a primary driver of the T2DM epidemic in Oman and was responsible for 56.7% of T2DM cases in 2020.[14] Intensive interventions targeting obesity

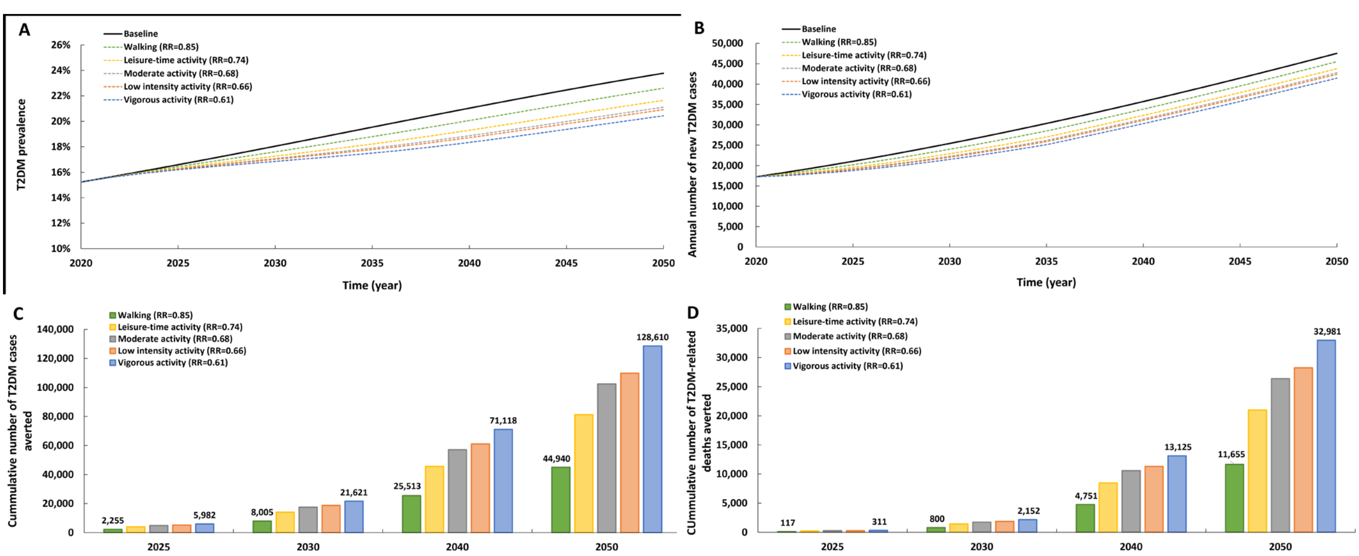


Figure 6 Projected impact of increasing the coverage of various physical activity intensities as an intervention among Omanis aged 20–79 years on (A) T2DM prevalence, (B) annual number of new T2DM cases, (C) cumulative number of T2DM cases averted, and (D) cumulative number of T2DM-related deaths averted. T2DM, type 2 diabetes mellitus.

are essential to altering the epidemic's course. Even moderate reductions in obesity could substantially affect T2DM incidence. Focusing on reducing obesity among women and younger people aged 25–39 years yielded particularly substantial reductions in T2DM incidence. This reflected the higher level of obesity among women and the fact that T2DM onset is occurring at a younger age in present-day Oman compared with previous years. As such, prioritizing these populations would mitigate the impact of T2DM on a larger scale among women and at younger ages in the overall population.

Implementing PA as an intervention, especially at vigorous intensity and with substantial coverage of 25%, is also impactful and could prevent over 14% of new cases by 2050. However, interventions aimed at reducing smoking and PIA prevalence had a generally modest impact. This reflects the fact that the effect sizes for smoking and PIA on T2DM are much smaller than the effect size of obesity on T2DM, that is, obesity is a stronger risk factor for T2DM. Moreover, smoking prevalence in Oman is lower than levels observed in most countries, and hence there is limited potential for benefit from a fall in prevalence.[41] Despite the potential impact of targeting key T2DM risk factors, the findings highlight the challenge of halting or reducing T2DM prevalence in Oman. Across all modeled intervention scenarios, except those targeting obesity reduction, T2DM prevalence continued to increase between 2020 and 2050 despite the interventions' impact on reducing T2DM incidence. Even in several scenarios targeting obesity, T2DM prevalence in 2050 was only marginally lower than in 2020 despite large reductions in T2DM incidence. This outcome results from the rapid aging and increasing life expectancy of Omanis.[14]

Oman has made progress in public health and in addressing some of the challenges of rising NCDs, such as reducing child mortality, extending life expectancy, and improving health system performance for NCDs.[14] Such a positive trajectory faces a threat from the rising T2DM epidemic, which is predicted to extensively and adversely impact healthcare and costs in the national health budget over the coming decades.[14 42] Thus far, the Ministry of Health has primarily prioritized curative clinical services, including specialized diabetes and obesity clinics with access to medications and specialists in primary healthcare centers.[43] Intervention programs that address obesity at a community level, such as health education programs or nutritional interventions, remain limited.[44] Step-count pedometers and dietary interventions for weight management involving one-on-one follow-up consultations have demonstrated somewhat promising outcomes in Oman warranting further expansion for long-term behavior change.[36 45 46] The recent implementation of structural interventions, such as a 50% excise tax on soda drinks and a 100% excise tax on energy drinks and tobacco products, as well as tax exemptions for businesses promoting PA, serve as useful upstream interventions to reduce obesity.[43 47–49]

Further expansion of such strategies combining individual-level/downstream and structural/upstream public health interventions is warranted as these can have, together, a substantial impact on both T2DM risk factors and T2DM burden, as demonstrated recently in a similar modeling study conducted in Qatar.[31] Emphasizing the prevention of modifiable risk factors and promoting environments that facilitate healthier lifestyle choices is an effective long-term strategy to reduce the T2DM burden.[50–52]

Relevant examples from the literature illustrate the impact of population-level lifestyle interventions that can be scaled up for primary prevention of T2DM.[17–22] For example, the Finnish,[18 20] Chinese,[19] Indian,[53] and American[17] diabetes prevention programs and the Diabetes in Europe-prevention using Lifestyle, Physical Activity and Nutritional Intervention (DE-PLAN)[54] have achieved substantial reductions in T2DM incidence, up to 40%, through the implementation of behavioral lifestyle changes focused on weight loss, particularly among individuals at higher risk of developing T2DM.[17–19] The National Health Service Diabetes Prevention Programme[55] has also demonstrated the impact of lifestyle interventions on T2DM incidence, achieving reductions of up to 10% at a population level in England. This program serves as an effective primary prevention approach, benefiting the wider population rather than solely the program participants.

Such lifestyle interventions, combined with structural strategies addressing food environments and systems, such as taxation, trade, urban planning, food marketing, labelling, and portion sizes, have demonstrated success.[51 56 57] For example, programs such as the French Ensemble, Prevenons l'Obésité des Enfants program,[58] Mexico's taxation on sugar-sweetened beverages,[56] and the comprehensive NOURISHING framework (which encompases: Nutrition label standards, Offering healthy food and menu choices, Using economic tools to address food affordability and purchase incentives, Restricting food advertising and other forms of commercial promotion, Improving the quality of foods in public institutions, Supports for breastfeeding, and Healthy food policies)[59 60] provide models of interventions. Oman could adopt similar measures by expanding its implementation of legislation on foods and beverages, or adopting fiscal approaches that promote the consumption of less energy-dense foods,[51] as well as health educational programs that align with Oman's National Policy for Diet, Physical Activity, and Health.[44]

All types of interventions aimed at reducing obesity and promoting PA warrant consideration to tackle the high burden of T2DM. Recent advancements in medications, including the development of glucagon-like peptide-1 agonists, such as liraglutide,[61 62] semaglutide,[63 64] and tirzepatide,[65] have demonstrated effectiveness in promoting weight loss and improving glycated hemoglobin levels among individuals with diabetes, pre-diabetes, and associated comorbidities. These pharmaceutical interventions can complement public health interventions for preventing and managing T2DM.[66] Additionally, the use of digital health tools, including dietary or PA-related applications, could aid in integrating T2DM prevention programs into the wider community.[67 68]

This study has limitations. The study did not encompass the expatriate population of Oman, focusing specifically on Omanis, the permanent and stable residents of the country. Expatriates in Oman typically arrive on work visas and remain for a specific duration in the country. Since the national risk factor surveys,[7–12 33] which constituted the primary input data for the model, did not include this transient population, they were not included in the analyses. The model assumed that individuals within a given population compartment maintain their statuses over time regarding obesity, smoking, and PIA unless the population prevalence of these factors changes, or an intervention specifically changes these statuses. An individual categorized as physically active in 2020 may have become physically inactive in subsequent years, but such changes at the individual level are not accounted for in the population-level structure of the model. The model also operated under the assumption of a constant rate of reduction in risk factors, whereas in real-world scenarios, this rate may fluctuate annually. Only three voluntary targets of the WHO's Global Action Plan for NCDs were modeled, while other targets, such as reductions in sodium intake or alcohol use, were not considered.

All population-based surveys available in Oman were used in the fitting of the model in this study. However, each varied in terms of the time point at which it was conducted, survey approach, design, geographic coverage, and methods used to ascertain T2DM and its risk factors.[7–12 33] The surveys also differed in their specific outcome definitions, potential selection and information biases, and response rates.[7–12 33] The mathematical modeling method accounted for differences in the representativeness of these surveys by adjusting the model to ensure the best fit of all data and weighting input data based on the level of confidence in each survey data point.

Since the estimates of the RRs of the effects of risk factors on T2DM onset and disease-related mortality are unknown in Oman, this study used RRs published in the global literature and derived from large, high-quality prospective studies pooled through global systematic reviews and meta-analyses.[4–6] The study investigated only the direct effects of PA on T2DM incidence, which may underestimate indirect effects such as that of PA on reducing obesity. Similarly, the interventions focused on the reduction of obesity in the population using a cut-off point of BMI≥30 kg/m^2, which may underestimate the impact of smaller reductions in BMI on T2DM incidence among individuals who may not have reached the obese cut-off, or reduction among those who are highly obese. Although the reduction of PIA and smoking affected T2DM incidence rather modestly, such reductions may have had a large impact on simultaneously reducing other NCD comorbidities associated with T2DM, such as cardiovascular disease and cancer. Thus, further supporting the importance of intervening on these T2DM-related risk factors.

Pilot interventions are warranted to assess the feasibility of the proposed strategies. Future research endeavors could include longitudinal studies evaluating the real-world effectiveness of the proposed interventions within Oman's distinctive sociocultural and socioeconomic context. Further, qualitative studies engaging key stakeholders in Oman could be conducted to provide insights on the feasibility of implementing and maintaining such public health interventions.

In conclusion, leveraging mathematical modeling, this study demonstrates that targeting key T2DM risk factors, particularly obesity, has the potential to substantially reduce the future burden of T2DM in Oman. Half of the T2DM cases projected by 2050 could be averted with reductions in obesity prevalence. PA as an intervention also significantly contributed to reducing T2DM incidence. These findings offer insights for policymakers, researchers, and health professionals in Oman and other countries grappling with the dual epidemics of T2DM and obesity. They highlight the importance of implementing population-level interventions targeting risk factors as a critical and indispensable strategy in addressing the rising burden of T2DM.

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