Economic model system of chronic diseases in Australia: a novel approach initially focusing on diabetes and cardiovascular disease

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Abstract: Chronic diseases affect around 80% of older Australians, are main causes of premature death, and account for 70% of health expenditures. The novel features, building and validation of an Australian prototype model-system which simulates interventions that target several chronic diseases are described. Chronic disease progression models are linked to a population-wide microsimulation projection model that accounts for demographic, socio-economic and health characteristics, comorbidities, health expenditures, quality of life. It estimates costs vs. benefits of simulated policy interventions. The outcome is a validated person-level prototype able to simultaneously model diabetes and Cardiovascular Disease (CVD). An illustrative model application is also presented.

Keywords: multiple chronic diseases; microsimulation modelling; economic analysis of health policy interventions; diabetes; CVD; cardiovascular disease.

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1 Introduction

Chronic diseases, such as cancer, heart disease, diabetes and arthritis, are strongly associated with morbidity, disability and premature mortality. Their rapid growth and by now epidemic proportions are considered to be major challenges for health policy, as are the ever-increasing related public and private health expenditures (WHO, 2005; Begg et al., 2007; Lopez et al., 2006).

In the Australian literature, there is considerable agreement that the prevalence of major chronic illnesses – such as the National Health Priority Area (NHPA) diseases of asthma, cancer, cardiovascular health, diabetes, injury prevention, mental health, arthritis and musculoskeletal conditions – is increasing, with population ageing and the 'obesity epidemic' being among the driving forces (Treasury, 2007). In 2001, around half of Australians aged 30 years or over had at least one NHPA disease. This proportion increased to close to 90% amongst those aged 65 years or more, with the majority of the disabled having an NHPA condition as the major cause of their disability (Walker et al., 2003). In relation to obesity, a major risk factor for chronic diseases, Australia ranks among the worst in the OECD countries (AIHW, 2006).

People with serious chronic diseases or disability have poorer quality of life and are considerably less likely to have jobs than other Australians (Walker, 2007a, 2007b; Bayliss et al., 2003; Oldridge and Stump, 2004; AIHW, 2004a, 2004b). Because lifestyle patterns, such as unhealthy diets, insufficient physical activity and excessive tobacco consumption, are major risk factors (Yach et al., 2004), chronic disease prevention and treatment are not only of medical concern, but also of social, family-level and personal interest (Seymour, 2007; Griffiths et al., 2007). Because quality of life has been shown to decline and health expenditures to increase with comorbidities (Walker, 2007a; Shwartz et al., 1996), a model-system allowing simultaneous consideration of several person-level chronic diseases, as well as the implications of a person having two, three or more of such chronic diseases in terms of poorer quality of life and greater treatment costs, is a significant advance on traditional single disease models. While this is important when analysing and ranking policy-relevant interventions, simultaneous consideration of several person-level chronic diseases, as well as the non-linear impact of comorbidities, is rare in the literature. This is despite the well-documented fact that many chronic diseases share common lifestyle risk factors. For example, Barr et al. (2007) found that abnormal glucose metabolism was not only a major risk factor for diabetes, but also a major contributor to cardiovascular deaths in Australia. Consequently, interventions to prevent Cardiovascular Disease (CVD) are a major focus when managing people with diabetes and pre-diabetes.

There has also been recognition in Australia of the need to better target policy interventions to the prevention of chronic diseases, so as to limit their negative economic, workforce participation, productivity and quality of life impacts. Recent initiatives announced in 2005, 2007 and 2008 include: improved management of chronic disease prevention and care; allocation of additional funds for the existing chronic disease strategies; recommendation to government by participants at the April 2008 '2020 Australian Summit' to make prevention a key health policy instrument. Also, better targeting policy interventions to the prevention of chronic diseases and their risk factors was recommended in the National Preventative Health Strategy (released in September 2009 by Australia's Minister for Health).

2 Aims

This paper describes the data and methods used in building the prototype of Australia's chronic disease model-system, *HealthAgeingMod*; highlights its novel features, which improve on earlier, more traditional modelling approaches; presents an illustrative application of the prototype.

The model-system aims to

- represent the total Australian population
- project into the future the prevalence of several individual-level chronic diseases
- account for the associations between diseases and their major health risk factors
- estimate the impact of chronic diseases on quality of life and on national health expenditures
- assess the rate at which individuals accumulate several major chronic diseases as they age
- carry out economic (including cost–benefit) analyses of policy-relevant interventions able to eliminate or delay the onset, as well as accumulation, of chronic diseases.

Overall, *HealthAgeingMod* aims to become a better analytical tool than what is currently possible with traditional models to identify the chronic disease interventions that are 'best value' in economic terms (e.g., quality of life or life expectancy gained for a given amount of expenditure).

3 Overview of model, novel elements and possible applications

3.1 Overview

Because no single data source and model could cover the broad-ranging factors, the complex interactions and the disease-level details required by the project, *HealthAgeingMod* is structured as a model-system (Figure 1). It represents the Australian population by a person-level 'Umbrella' model that is linked to disease-specific sub-models. Its current prototype considers a nationally representative sample of individuals, and covers CVD and type-2 diabetes as single per person diseases, as well as these two diseases being present in one individual. The model-system, programmed in the SAS language, may in future be extended to other chronic diseases, such as mental health, arthritis and cancer.

There are three key reasons for initially choosing CVD and diabetes. First, they are major contributors to Australia's total burden of disease (Begg et al., 2007). Second, CVD and high mortality from CVD are a common complication of diabetes. Third, CVD and diabetes share common risk factors such as physical inactivity, obesity and high blood pressure.

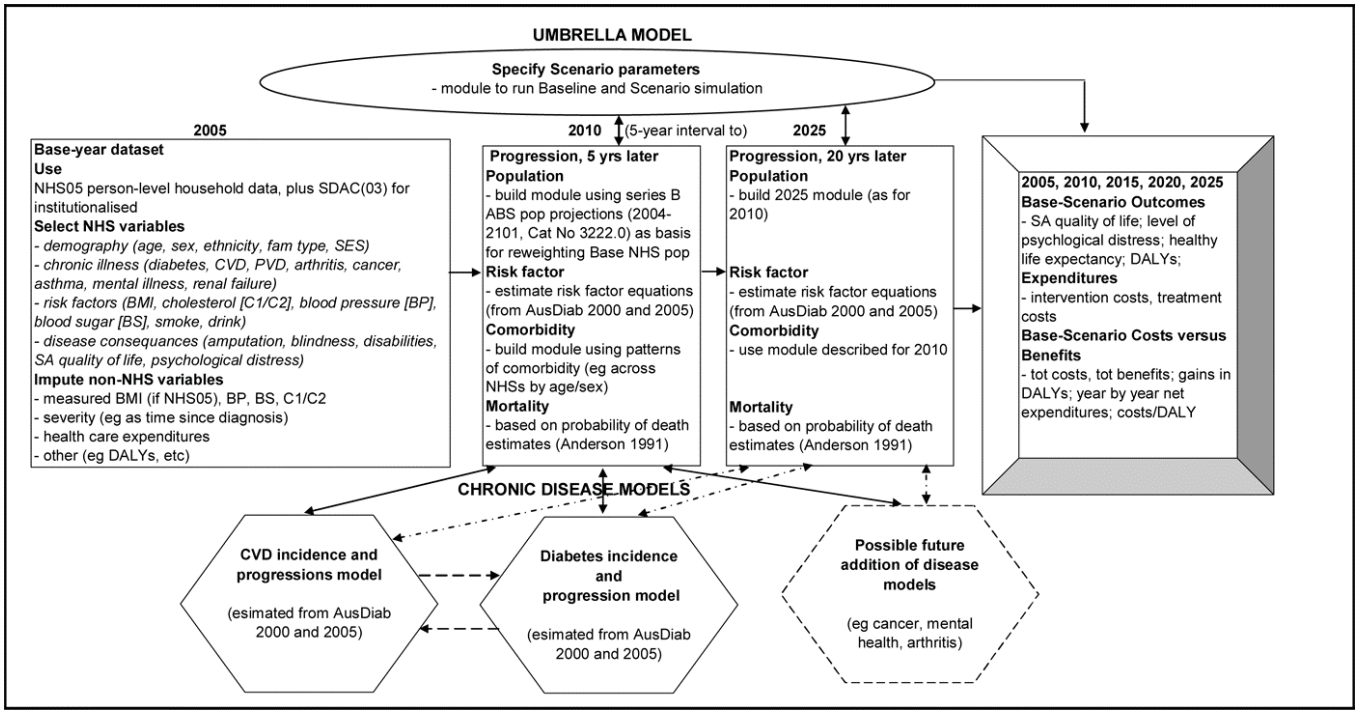
Building *HealthAgeingMod* required:

a a set of nationally representative person-level demographic, socio-economic, lifestyle and health variables at a particular point in time

b the projection into the future of risk factors; disease-specific incidences and prevalences; progression of individual-level chronic diseases and comorbidities.

Part (a) involved bringing together nationally representative individual-level cross-sectional data from several sources in a coherent manner. This needed to be complemented by Part (b), which required use of disease-specific longitudinal data to estimate the incidence and progression of chronic diseases.

Figure 1 The prototype chronic disease model-system



We chose to model (a) and (b) separately, and then linked the two parts, so that the 'big picture' as well as the 'detail' associated with the tracking of individuals' health could be studied simultaneously. A major benefit of such a model-system is that it can be used to assess policy proposals in terms of broad population-wide variables (e.g., worse or improved obesity patterns; choice of screening options; lesser health inequalities), as well as of medical treatment choices (e.g., surgery replaced by new, improved – but costly – pharmaceuticals).

One key default assumption in the model-system is that, in the absence of intervention policies, continuation of past patterns is an appropriate way of predicting the future. Another is that, under intervention scenarios, the lesser the numbers with chronic diseases the lesser will be the related expenditures. This latter assumption means that the prototype does not account for the upward cost pressures arising from likely future improvements in medical technology (Treasury, 2007). The impacts of these default assumptions can, however, be studied through sensitivity testing.

Another default assumption is that those already with diabetes in the base year (2005) will continue to have diabetes in the projection period, since at this time only

obesity surgery can reverse diabetes. Another assumption is that all persons – whether with or without CVD in 2005 – can have a major CVD event in the projection period.

Section 4 provides a summary of the various Figure 1 model elements. Further information, including details of the model-system's assumptions and limitations, are in Walker et al. (2010).

3.2 Novel model elements

While many individual-level population-based models had been, or are being, developed worldwide, most fall within the tax and social security fields (see review in Zaidi and Rake, 2001). The few that account for health tend to be either of the large socio-economic model type, which use a broad indicator of health as a covariate within the larger picture, or of the disease-specific model type, designed to study treatment options so as to assess their cost effectiveness (see reviews in Lymer (2009), Walker (2009)). Some simultaneously account for several diseases, such as the Population Health Model (POHEM) developed at Statistics Canada. However, so far, POHEM has been mainly used for single disease applications (Lymer, 2009). These applications tend to arise from disease-specific projects that add to the existing model a new module on the disease to be studied (Spielauer, 2007). Examples of POHEM's single disease applications include Evans et al. (1997) for lung cancer and Kopec et al. (2010) for arthritis.

Other applications of microsimulation models, which simultaneously consider multiple chronic diseases, tend not to account for the non-linear nature of comorbidities. Examples include OECD (2009), which ranks broad-level obesity-related interventions across selected OECD countries (e.g., in schools, workplaces, or by primary care providers) and Goldman et al. (2004), which takes as inputs the likely breakthroughs predicted by US 'Medical Technical Expert Panels' to estimate, for the elderly in the USA, future Medicare cost patterns.

By comparison, the first policy-relevant application of *HealthAgeingMod* proposed by Australian health policy developers concerns interventions that involve screening for two major chronic diseases and their common risk factors, followed by several possible post-diagnosis treatment paths. The aim is to identify single and combined diseases, as well as account for the non-linear nature of comorbidities. The screening will test for CVD, diabetes and their risk factors among 40–74 year olds. High-risk status or diagnosis will be followed by several possible medically identified treatment and prevention paths. With *HealthAgeingMod's* detailed modelling of comorbidities, the scenario to Baseline comparisons will include estimates of the delays in the onset of CVD or diabetes, as well as delays in the onset of a second chronic disease. This latter feature will be particularly important once other chronic diseases are added to the model (e.g., depression, arthritis, cancer). While this realistic scenario is planned for a future publication, the illustrative *HealthAgeingMod* application in Section 6 provides an initial insight into the types of outputs that can be obtained at the prototype stage.

Overall, important novel elements of *HealthAgeingMod* are that it covers

- both the broad socio-economic and the detailed disease-specific aspects
- accounts for several chronic diseases, modelling the onset and progression of each, and linking these to their common risk factors.

It thus allows simulation of complex chronic disease policy reform proposals that can combine medical treatment options – e.g., a new drug being used for diabetes or new hospital procedures for stroke – with lifestyle-changing options – e.g., diet or exercise – and with socio-economic reform options – e.g. improving the health of poorer population groups.

A further novel element of *HealthAgeingMod* is its ability to assess the full benefits of interventions that target risk factors common to several chronic diseases. For example, in traditional models (Eastman et al., 1997a, 1997b; Clarke et al., 2004; Colagiuri and Walker, 2008), the estimated benefits from single-disease-prevention interventions are limited to that disease itself, even when the intervention affects a risk factor – such as obesity – that is common to several chronic diseases. *HealthAgeingMod* can simultaneously analyse risk factor interventions that impact on multiple chronic diseases, so its benefit estimates are more comprehensive than those of traditional models, resulting in more accurate findings. At the policy level, availability of such an improved model is more likely to encourage consideration of more complex interventions than in the past.

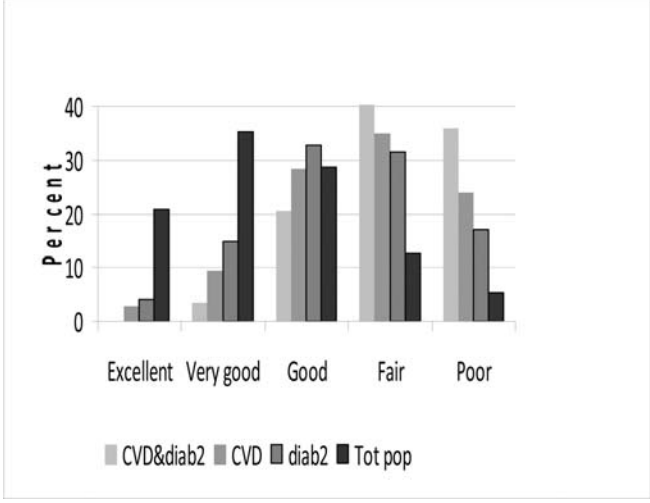
Another novel element, which is difficult to handle analytically and to place in a nation-wide context, is the estimation of the number of chronic diseases that individuals are more likely to accumulate with age. The difficulty arises in part from national health data collections tending to focus on single diseases, and in part from data on number of diseases at the person-level being not only scarce, but also difficult to model.

Figure 2 and Table 1 illustrate the relevance of this latter element for the diseases and comorbidity modelled in the prototype, i.e., persons with type-2 diabetes only, with CVD only and with both CVD and type-2 diabetes.

Figure 2 is based on data from Australian Bureau of Statistics' National Health Survey (ABS, 2006a, 2006b, 2006c, 2006d), which asked its 25,906 respondents if they had been told by a doctor or a nurse that they had NHPA illnesses, including diabetes and CVD. The figure shows that, in 2005, a much higher proportion of Australians aged 15 years or more self-reported excellent or very good health, than did persons with either CVD, type-2 diabetes or with both these illnesses. A striking finding is the considerably greater negative health impact of having both CVD and diabetes than having only one of these illnesses. That is, persons with both CVD and diabetes had a much greater proportion reporting poor health (36%) than persons with

only one of these diseases (24% for CVD and 17% for type-2 diabetes), or the population generally (5%).

Figure 2 Proportions of 15+ year olds by disease and perceived health state, 2005



Source: NHS05 (ABS, 2006b)

Table 1 Healthcare costs for people with NHPA diseases, 2000 prices

Description	*Average cost per person per year* (*Australian dollars*)
Single NHPA	
Cardiovascular Disease	4006
Cancer	2478
Asthma	1502
Diabetes	1289
Multiple NHPAs	
2 Cardiovascular Disease and diabetes	6283
2 Cancer and Cardiovascular Disease	8526
2 Diabetes and mental illness	2738
3 Cancer, Cardiovascular Disease and mental illness	10,090
4 NHPA conditions	12,405
5 NHPA conditions	14,337

Source: Department of Health and Aged Care (2000)

Table 1 indicates that there is also a cost difference associated with comorbidities, including having both CVD and diabetes. It shows that the cost of treating individuals with NHPA illnesses increases with the number of diseases a person has, and that this increase is greater than what a simple sum of the single-disease costs would suggest. For example for CVD and diabetes, the single yearly disease costs of AU$4006 and AU$1289 sum to AU$5295, which is less than AU$6283, the cost of treating a person with both CVD and diabetes. These Australian findings are in line with those of Wolff et al. (2002) in the USA.

Overall, the modelling of the above-mentioned novel elements in *HealthAgeingMod* is expected to encourage a re-focus of chronic disease policy initiatives towards multiple chronic diseases and away from single diseases. It is also expected to considerably improve the accuracy of the economic evaluations associated with the related intervention proposals.

3.3 Possible model applications

Scenarios that could be analysed using *HealthAgeingMod* include:

- simulating the impacts of various combined lifestyle and disease-specific treatment options, leading to their ranking through cost–benefit and cost effectiveness analyses
- simulating the impact of various lifestyle interventions (e.g., obesity/overweight, smoking, alcohol consumption) on health outcomes and healthcare costs associated with single as well as multiple chronic diseases
- comparing such analyses across chronic diseases individually, and with the diseases combined – the aim being to identify key comorbidity patterns and the intervention points most likely to be effective.

Use of the model-system to inform decision-makers can help identify the most effective policy interventions to reduce the prevalence and severity of NHPA diseases. Following implementation of such policies, considerable benefits would be expected for Australians in terms of better health, productivity and well-being. Health expenditures would be lower, the pool of skilled people entering or remaining in the workforce would be greater, and living independently would be a possibility for a greater number of the frail old.

4 Data and methods

4.1 Data

Main data sources used were:

- Basic and Expanded CURF (confidentialised unit record files) of the cross-sectional and nationally representative 2005 National Health Survey (NHS05) (ABS, 2006b, 2006c) for the Umbrella model's base-year data. Further details on NHS05 are in Appendix A.
- Unit record data from the longitudinal Australian Diabetes, Obesity and Lifestyle Study (AusDiab_2000 and AusDiab_2005) (BakerIDI Heart and Diabetes Institute, 2001, 2006; Magliano et al., 2008). Because AusDiab is not nationally representative, the longitudinal nature of this data source could only be used as a basis for estimating the probability of disease incidence. For type-2 diabetes, we used data from the main AusDiab survey. For CVD incidence, we used its

CVD sub-survey, which has data on hospital treatment of: stroke; Coronary Heart Disease (CHD) and myocardial infarction; coronary artery bypass graft surgery; percutaneous transluminal coronary artery angioplasty. Further details on AusDiab are in Appendix B.

- Australian Bureau of Statistics population projections (ABS, 2005) as the basis for the model-system's population projections by 5-year age group and sex.
- Health expenditure statistics in Clarke et al. (2008) for 'default' per person per year CVD input costs AIHW (2005, 2008, 2009a) and ABS (2005, 2006b, 2006e, 2008, 2009) for validation benchmarks (in Table 5); and Department of Health and Aged Care (2000) for the 'default' per year input cost of treating diabetes without complications and of the higher than the summed treatment costs for those with both CVD and diabetes. The 'default' unit costs are summarised in Table 2. This table distinguishes between non-fatal and fatal costs and accounts for the higher cost of treating patients with comorbidities – i.e., with both CVD and diabetes – by increasing the summed single-disease costs, as default, by 20%.
- Benchmark data for validating the prototype in AIHW (2005, 2008, 2009a,) and ABS (2005, 2006b, 2006e, 2008, 2009). Table 5 details which data source was used for which part of the validation process.

The NHS05 survey population provided the base-year population for *HealthAgeingMod*. The individual-level variables extracted included age, sex, socio-economic status, education level, health risk factors (blood pressure, cholesterol, blood glucose level, Body Mass Index (BMI), whether smoking and exercise level), as well as whether the individual has been told by a doctor or nurse if they had diabetes, CHD or a stoke event.

AusDiab was the main source of data for estimating equations of the probability that a person would acquire diabetes, CHD or stroke as a function of their risk factors. The linkages required between these two data sets were achieved by re-arranging all demographic, socio-economic, risk factor and disease variables so that their definitions were comparable across data sets. The AusDiab-based probability equations were then applied to each NHS-based individual without the disease. Next, these probabilities were compared with a random number (Monte Carlo method), to determine whether the person would acquire the disease in the projection years. Further details are in Section 4.2.

Table 2 Diabetes and CVD 'default' total costs per person in prototype

	Total cost per person (AU$)	*per annum* (1999–2000 dollars)
	Non-fatal	*Fatal*
Diabetes without complications	1289*	
CVD events (at time of event)		
CHD (incl angina, heart failure)	13,000	10,000
Stroke	13,000	10,000
CVD post event (subsequent years)		
CHD (incl angina, heart failure)	3500	10,000
Stroke	3500	10,000
Diabetes with CVD	20% above the sum of the single-disease costs#	–

*Department of Health and Aged Care (2000); #From Table 1.

Source: Clarke et al. (2008) for CVD costs

4.2 Methods

Because the Umbrella model is based on microdata and uses *microsimulation methods*, its focus is on the individual. This allows examination of the impact of policy changes in far greater detail than is possible with more traditional grouped-data-based approaches. For example, if the groupings embedded in the group-model are by age-band and sex, then the simulation results cannot be disaggregated by other variables, such as socio-economic status, or the number of diseases (i.e., comorbidities) people have, the latter being a major focus of *HealthAgeingMod*.

The Umbrella model accounts for Australians' demographic, socio-economic, health-risk-factor and health status characteristics; the number of chronic diseases (comorbidities) they have; their quality of life; the related health expenditures. Its base-year population comprises the 25,906 individuals of the NHS05 CURF (Appendix A). Attached to each base-year person by ABS is a 'weight' variable, which indicates the number of Australians represented by that person. Application of these 'weights'

then allows survey estimates to be summed to the national level.

Other standard micro simulation methods used include imputation of variables not in NHS05, alignment of the model to aggregate external benchmarks, and application of the Monte Carlo method to select from among high-risk individuals those with new diabetes or with new CVD event(s) (Walker et al., 2010). Because the Monte Carlo method introduces randomness into the model results, it is customary to estimate the related stochastic variation through execution of several model runs until the results 'converge' within set bounds. However, because with microsimulation models, the number of repetitions required to achieve 'convergence' was found to be relatively small – four runs in Pudney and Sutherland (1993, 1994) and six runs in Walker et al. (2006a, 2006b) – this feature has not been used at the prototype stage, but is planned for the final model-system.

The diabetes and CVD sub-models are econometric incidence/progression models. They predict changes over time in the health states of each individual in the Umbrella model's base-year data. They also predict the progression of risk factors, as well as who will become 'newly diagnosed' with diabetes and who will have at least one hospital CVD event in the 5-year period under consideration. Next, the model-system accounts for across-disease linkages (e.g., whether CVD is a single chronic disease or is a complication of diabetes).

a Choice of data sources

To estimate the incidence of diabetes, the initial intention was to use the United Kingdom Prospective Diabetes Study Outcomes model (Clarke et al., 2004). This choice was made because during the first couple of years of our project there were no Australian longitudinal data for diabetes (Walker et al., 2008). However, once both the 2000 and 2005 waves of AusDiab became available, considerable differences between the UK and Australian data emerged. For the same 'lack of longitudinal data' reason, we initially envisaged using the US-based (Anderson et al., 1991) equations for estimating CVD incidence (and deaths). However, when CVD data in both waves of AusDiab became available, once again considerable differences emerged between the overseas and Australian incidence patterns.

For these reasons, in the prototype we used the 2000 and 2005 waves of the AusDiab survey to estimate the probability of a model-system-individual being diagnosed with new diabetes or of having a new CVD event over a particular 5-year projection period.

Unlike the NHSs, which with very few exceptions only have self-reported data, AusDiab has both self-reported and measured data. After comparing the AusDiab aggregates with official external benchmarks, we chose for diabetes AusDiab's measured data, and for CVD its measured and medically verified data. These measured data better matched external benchmarks than did AusDiab's self-reported data.

For CVD mortality, we were not able to use AusDiab data because only a small number of AusDiab participants died between the 2000 and 2005 waves, and these were not sufficient for regression-based estimations. Thus, for CVD deaths we used the initially envisaged (Anderson et al., 1991) equation. The reason for this choice was that the Anderson parametric statistical model is still seen internationally as providing the best CVD estimates. Indeed, the current National Health and Medical Research Council guideline (2009) recommends using the Anderson et al. (1991) equations in Australia.

b Risk factor progressions over time

Prior to estimating new cases of diabetes and CVD, *HealthAgeingMod* progresses individuals' risk factors of blood pressure, cholesterol, blood glucose and BMI. Future values for each of these risk factors are predicted through use of multiple regression equations based on the 2000 and 2005 waves of AusDiab (Walker et al., 2010, Section 5.2).

c Disease progression over time

To estimate the probability of new diabetes, new CHD and new stroke events we built econometric incidence/ progression models. For these, we used the PROC LOGISTIC command of SAS, based on Fisher's scoring optimisation technique (Lee, 1974; McCullagh and Nelder, 1989).

Briefly, the numbers with new diabetes, CHD or stroke were estimated:

- by using AusDiab data across the 2000 and 2005 waves to obtain equations of the probability of a state change from 'without' to 'with' the condition
- next applying the above-mentioned equation to each individual in the model-system's NHS05-based population, to attach a probability of acquiring the condition in the projection period
- comparing that probability with a random number through the Monte Carlo method to ascertain whether that model-system individual, with his or her probabilities, will actually acquire the new condition.

Table 3 reproduces the AusDiab-based coefficients embedded in *HealthAgeingMod* for estimating the probability of new diabetes and new CVD, as well as the Anderson et al. (1991)-based CVD death coefficients. As noted earlier, the risk factor variables in the table were rearranged so that they are as comparable as possible across the main data sets used (i.e., NHS and AusDiab).

Table 3 Probability of CVD death# and diabetes/CVD incidence*– coefficients

CVD death variables	*CVD death*	*CVD/diabetes incidence variables*	*CHD*	*Stroke*	*Diabetes (type 2)*
θ_0	0.8207				
θ_1	–0.4346				
β_0	–5.0385	Constant	–10.0208	–9.5504	–23.1995
Female	0.2243	Female	–1.0312	–	0.8345
log(age)	8.2370	Age	0.0456	0.0498	–0.0199
$(\log(age))^2$	–1.2109				
log(age) × female	–				
$(\log(age))^2 \times$ female	–	sugar level (hba1c)	–	–	3.3440
log (Blood pressure)	–0.8383	blood pressure (SBP)	0.0163	–	0.0112
Cigarettes (Y/N)	–0.1618	cigarettes_current/ex (SMOK)	–	–	0.4030
log(total-C/HDL_C)	–0.3493	Body Mass Index (BMI)	0.0507	0.0271	0.0405
Diabetes	–0.0833	CVDhist	–0.4775	–	–
Diabetes × female	–0.2067	EDlevel	0.3456	–	–
ECG-LVH^	–0.2946	Concordant	82.1%	56.1%	83.1%

*Authors' estimates from AusDiab data, all variables significant at 0.05 level or less; ^ not used.

Source: #Anderson et al. (1991)

The AusDiab, or Anderson variables found statistically significant were:

Female	0 for males; 1 for females
Age	Single years
Blood glucose	Measured HbA1c (%)
Blood pressure (SBP)	systolic blood pressure (mmHg)
Cigarettes (SMOK)	1 if current or ex regular smoker; 0 otherwise
Body Mass Index (BMI)	Measured weight/height 2 (kg/m^2)
total-C/HDL_C	Total/HDL cholesterol (mmol/l)
Diabetes (for new diabetes)	Measured blood glucose concentration (%)
Diabetes (for CVD deaths)	1 if self-reported type 2 (told by doctor/nurse); 0 otherwise
CVDhistory	1 if event prior to 2000 (told by doctor/nurse); 0 otherwise
EdLevel	1 if has University or other further education; 0 otherwise

Exercise, high cholesterol and having (measured) pre-diabetes were initially also included in the AusDiab-based equations, but were not statistically significant. The list of initially included predictor variables for new diabetes may not exactly match that in other publications, such as Magliano et al. (2008). This is because in our case we could only include variables that were available in both AusDiab and NHS05. As seen earlier, AusDiab was used to estimate disease probability equations, which were then applied to the individuals in the model-system's NHS05-based population.

For the probability pi of a new CHD event, stroke or diabetes, the estimated logistic regression equations were of the form:

$$p_i = \exp(\eta)/(1 + \exp(\eta))$$

where

$$\eta = \text{constant} + a \times \text{female} + b \times \text{age} + c \times \text{HbA1c} + d \times \text{SBP} + e \times \text{SMOK} + f \times \text{BMI} + \cdots + h \times \text{EdLevel}.$$

For the probability p_i of CVD death over the next five years, the Anderson et al. (1991) equation was:

$$p_i = 1 - \exp(-\exp(\eta))$$

with η computed as:

$$\mu = \beta_0 + a \times \text{female} + b \times \log(\text{age}) + c \times (\log(\text{age}))2 + \cdots + \text{diabetes} \times \text{female}$$

$$\text{sig} = \theta_0 + \theta_1 \times \mu$$

$$\text{sigma} = \exp(\text{sig})$$

$$\eta = (\log(5) - \mu)/\text{sigma}.$$

Once these p_i had been estimated, we applied the Monte Carlo method in the model system by drawing a random number, z, from a uniform distribution over the interval [0, 1] and comparing it with the relevant p_i. That is, we allocated an actual event to the person being considered if his or her p_i was greater than z.

Table 3 presents the coefficients of these equations, which are generally as expected. However, there are a few counter-intuitive results, which are not uncommon in studies of this kind. One is the negative coefficient

between cigarettes and CVD death. This is as reported in Anderson et al. (1991). Another is the negative coefficient between CVDhist with CHD, which could possibly arise from the considerable definitional differences between CVDhist (self-reported as diagnosed by doctor/nurse) and CHD as measured across the 2000 and 2005 AusDiab waves (i.e., major hospitalised events only). Should better data, including better benchmarks, become available in future, such data may provide a basis for re-estimating the above-mentioned equations.

As in Australia there are no external longitudinal data similar to AusDiab, checking the predictive ability of the above-mentioned equations could only be carried out at a broad level. We did this within Section 5, on the validation of *HealthAgeingMod*. The external benchmarks used were official statistics from the ABS and the AIHW (Table 5).

Table 4 Australian population by age, 2010 and 2025

	ABS	*Population projections*	
	2010	*2025*	
Age	(*'000*)	(*'000*)	*% change*
0–14	3963	4083	3.0
15–29	4361	4424	1.5
30–44	4527	4960	9.6
45–54	3008	3170	5.4
55–64	2546	3026	18.8
65–74	1645	2614	58.9
75–84	1013	1734	71.2
85+	404	648	60.4
All	*21,467*	*24,661*	*14.9*

Sources: ABS (2005) Series B

To project Australia's population up to 20 years ahead, the Umbrella model's projection module 'ages' the base-year population by age and sex at 5-year age intervals. It achieves this by using the optimising 're-weighting' method embedded in the ABS's GREGWT software. This software changes the original sample survey weights, so that the new weights it outputs line up with the population projections forecast by ABS (2005). Table 4 summarises the population 'targets' used in re-weighting the prototype for 2010 and 2025. It shows that, over that period, Australia's population is expected to increase from 21.5 million to 24.7 million (14.9%) and that most of the increases will be among the 65+ age group (the numbers for 75–84 year olds having been projected to increase by 71%).

Finally, the model system makes use of standard cost-benefit and cost effectiveness methods (Jena and Philipson, 2007). Its 'Cost–benefit module' – Figure 1 – is first run in 'default' mode (i.e., no policy change). This provides the Baseline simulation. Next, the model is run in 'Scenario' mode (i.e., with the policy change). The 'Cost–benefit module' then compares the Baseline and Scenario health outcomes in terms of Disability-Adjusted Life Years (DALYs) avoided, as well as the Baseline to Scenario differences in terms of monetary benefits and costs. Colagiuri and Walker (2008) present an example of this process for a diabetes prevention and care scenario using an earlier model.

5 Validation

Validation against external benchmarks for the Baseline simulation is summarised in Table 5. External benchmarks included publicly available ABS and AIHW data between 2005 and 2008. In addition, availability late in 2009 of the 2007–2008 NHS unit record files allowed this later survey (NHS08) to be used as a benchmark for some of the prototype's projection period outputs.

Table 5 Validation of prototype

(1) Base-year characteristics, 2005			
	Prototype	*Benchmark*	*Source of benchmark*
Total population – 2005	19,681,539	20,328,600	ABS (2006e)
	From NHS05 survey	ABS population data	
Diagnosed type 2 diabetes – without CVD	528,928	581,000	
– with CVD (No)	*50,321*	(types 1 and 2)	AIHW (2008)
Total	*579,249*		
Diab treatment costs (AU$million, 2000) – without CVD	746		
– with CVD	*838*	1664	AIHW (2005)
Total	*1,584*		
CVD^ – without diabetes (No)	242,958	242,958	ABS (2006b)
CVD treatment costs (AU$million, 2000)	3209	3944	
	(without diabetes)	(with diabetes)	AIHW (2005)**

Table 5 Validation of prototype (continued)

(2) Projections – 2005 to 2010 (*5year period*)				
		Prototype	*Benchmark*	*Source of benchmark*
Total population – 2010		20,181,395	21,472,282	ABS (2005)
New diabetes: (No)		429,198		
All diabetes: (No)	– without CVD	924,851	813,860	ABS (2009)
	– with CVD	50,068	(with or without CVD)	growth 2005 to 2008 pro-rated to 2010
	Total	*974,719*		
– treatment costs (all diabetes)	– no CVD	3,753		
	– with CVD	1,134		
	Total	*4,887*		
CVD, fatal: using US data (Best predictor internationally) in Prototype (No)		200,831 (over 5 years, or 57,828 pa)	156,060 (over 5 years)	ABS (2008) (CVD deaths in 2006*5)
CVD* event, non-fatal, in 2010 (No)		289,140	238,485 (2006–2007+)	AIHW (2009a)^^
CVD treatment costs (AU$million)				
: fatal hospitalised CVD event		1,317		
: non-fatal CVD event without diabetes		5,856		
: treatment of those with CVD history only		4,142		
Total		*11,315* (over 5 years, or 2,263 pa)	*3,944* (inc CVD with diabetes)	AIHW (2005)**

*Myocardial infarction ; stroke; coronary artery bypass graft; percutaneous transluminal coronary artery angioplasty.

**AIHW 2005 (Table 5) on recurrent expenditures for CVD pharmaceutical and hospital events.

+CHD, stroke, heart failure; ^ Ischaemic heart disease and stroke; ^^ Heart. Stroke and Vascular Disease.

Source: Prototype Baseline simulation

(a) For the *base year*, Table 5(1) generally shows a good match with external benchmarks. That year the weighted number of Australians with type-2 diabetes was 579,249 in the prototype, which is close to the 581,000 figure published for the total number of persons with diabetes (type 1 and type 2) in 2005 by AIHW (2008). The prototype's estimate of the costs associated with diabetes and its complications (AU$ 1584 million, in 2000 dollars) was close to the AU$ 1664 million published by AIHW (2005). Such a close match is remarkable, given that the model-system's base data are from a household survey, which excludes people in hospitals and nursing homes, while the AIHW data are full-population based.

The exact match in the number of Australians who had CVD without type-2 diabetes in 2005 – 242,958 persons – arises because the benchmark (ABS, 2006b) are also the data from which the prototype's base-year population is drawn. This arises because the NHS05 CURF is the only 2005 source from which the total numbers with CVD, but without type 2-diabetes, can be estimated.

The prototype's 2005 CVD treatment cost of AU$3209 million is below the benchmark of AU$3944 million. This is as expected, given that the prototype considers a smaller subset of CVD conditions than does the benchmark. The latter for a broader NHPA-defined CVD group accounts for all hospital and pharmaceutical expenditures, as defined in Australia's NHPA documents.

(b) Validation of the prototype's projections from 2005 to 2010 – Table 5(2) – proved considerably more difficult. As noted earlier, availability in late 2009 of unit record data from NHS08 provided some benchmarks for 2010. Where relevant, we pro-rated the NHS08 data to 2010 in a linear fashion. However, the different definitions of CVD in NHS and AIHW benchmarks – i.e., self-reported doctor/nurse diagnoses covering all with CVD – caused mismatches with the projections, which are based on AusDiab measured data accounting only for a few major hospitalised CVD events.

Table 5(2) shows that the prototype's 2010 population (20,181,395) is somewhat less than the corresponding ABS-published projection (21,472,282). This is expected as the prototype's 2010 population is based on a reweighted NHS05 survey population and is thus not exactly the same as the ABS-published full population projections.

The diabetes and CVD projections in Table 5(2) arise from the AusDiab-based incidences that were embedded in the prototype (Section 4). The number of persons with newly diagnosed type-2 diabetes projected between 2005 and 2010 was 429,198 and, for this incidence statistic,

we have no external nationally representative benchmark data. For the total number with diabetes in 2010 – assuming that those with diabetes in 2005 will still have diabetes five years later – the prototype's estimate was 974,719 persons. This is 20% above the 813,860 benchmark obtained by pro-rating the numbers in NHS08 to 2010. On the basis of AIHW (2009b), which concluded that the NHSs were the best benchmarks for diabetes prevalence, we plan to align the final version of *HealthAgeingMod* to NHS-based prevalence benchmarks.

For non-fatal CVD, the number with new CVD hospital events projected over the five years was 289,140 – or 57,828 new events per year. It is difficult to compare this estimate with the only benchmark (AIHW, 2009a) we could find, which indicates 238,485 Australians with CHD, stroke or heart failure in 2007–2008, whether hospitalised or not. Nevertheless, the comparison is reassuring because, as expected, the numbers predicted by the prototype for major hospital events (57,828 a year) are considerably lower than the benchmark, which is for all with CVD.

The CVD cost comparisons also suffer from the problem of non-availability of directly comparable benchmarks. Nevertheless, the comparisons are once again reassuring given the considerably lower costs predicted by the prototype for the sub-group of major hospital events than for the broader all with CVD group.

Overall, the prototype's outputs broadly line up with patterns expected from published external statistics. What is important to note is that such under or overestimates will be consistent in both Baseline and Scenario simulations, making the differences between Base and Scenario much more robust than the separate Base and Scenario totals. The importance of such differences is illustrated in Section 6.

6 Illustrative simulation

To study the health and health cost impact of population ageing in Australia (Table 6), in Scenario S1 we used the prototype to estimate the number of Australians with diabetes only in 2010, with new CVD hospital event(s) only since 2005, and with both diabetes and CVD. Next, in Scenario S2, we estimated what the health and health cost difference would have been had, in 2010, Australia had the population structure predicted for 2025. Moving from S1 to S2 resulted in the proportion of Australia's 60+ year olds to rise from 17% to 26% of the total population – a situation similar to Japan's 60+ proportion at present, which is close to 27%.

Table 6 Scenario S1: Projections from 2005 to 2010 with Prototype; Scenario 2: re-basing above to 2025 population

	Scenario S1 *2010 population structure*	*Scenario S2* *S1 with 2025 population structure**	*Difference* *S2 to S1*
Persons (numbers)			
– Diabetes only	951,706	1,570,000	+618,294
– Diabetes+CVD event	50,749	109,782	+59,033
– CVD event only (non-fatal)	285,222	501,670	+216,448
All with Diabetes and CVD	*1,287,677*	*2,181,452*	*+893,775*
Expenditures (AU$ million)			
– Diabetes only	4816	8166	+3350
– Diabetes+CVD event	1128	2425	+1297
– non-fatal CVD event only	5767	10,111	+4344
– fatal CVD event only	1317	3385	+2068
Total CVD Plus Diabetes Costs	*13,028*	*24,087*	*+11,059*

*Prototype estimates aligned to Australian Bureau of Statistics projections: a population of 21.5 million in 2010 and 24.7 million in 2025.

Source: Prototype simulations

Table 6 illustrates the advantages of our person-level prototype, compared with traditional group or single disease models. With *HealthAgeingMod*, we were able to separately identify persons:

- With *diabetes only* (pre-existing as well as new diabetes), estimating 618,294 more persons under Scenario S2 with only type-2 diabetes than under S1 (an additional AU$3350 million in treatment costs over the five-year period, or AU$670 million per year).
- With *diabetes as well as a* CVD hospital event, estimating 59,033 more persons with both these conditions (an additional AU$1297 million in treatment costs over five years, or AU$259 million per year). Of particular interest is that, with the older population of S2, the numbers in this comorbidity group more than doubled (from 50,749 to 109,782).
- With *non-fatal CVD hospitals event only*, there would be 216,448 more persons with CVD only (an additional

AU$ 4344 million in treatment costs over the five years, or AU$ 869 million per year)

- deaths in hospital as a result of their CVD event would cost AU$2068 million over the five years, or AU$414 million per year.

Table 6 shows that the estimated costs for diabetes and CVD hospital events would be AU$11,059 million greater over five years (or AU$ 2212 million per year) if the Australian population had the ABS-projected 2025 age sex structure, rather than the prototype's projected 2010 age-sex structure.

In summary, the additional costs for diabetes and CVD hospital events arising from ageing – that is 26% of the population being aged 60+years rather than the 2010 17% – is estimated at AU$2212 million per year. With the complex unit record-based model-system, we were also able to decompose this total into 39% for non-fatal CVD events only, 30% for diabetes only, 19% for fatal CVD events and 12% for both CVD and diabetes.

In these illustrative simulations, we only accounted for change in one factor, the age structure of the Australian population. However, population ageing is known not to be the main reason for the very rapid increases in health expenditures of concern to governments worldwide. The key drivers of health cost increases have been, and are expected in future to be, the rapid rises in the unit health costs arising from improvements in medical technology, together with Australians' expectations to have access to these (Treasury, 2007).

7 Conclusions

This paper on the *HealthAgeingMOD* prototype shows that the tasks set for the chronic disease model-system are complex. It also shows that the building of the model-system requires considerable creativity and innovation: in data collection, selection and linkage to better account for the common elements and complex interactions across chronic diseases; in the approaches and methods chosen for building the Umbrella model and the disease-specific sub-models; in the broadening of the boundaries of the social and health indicators considered. These latter include individuals' lifestyles; a person-level life-course approach; consideration of personal characteristics as well as medical treatment options and costs; interventions that focus on prevention as well as on medical treatment.

The main outcome to date is a validated prototype, which uses a novel method for the rarely attempted task of simultaneously modelling multiple chronic diseases, as well as comorbidities.

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Appendix A: National Health Surveys (NHS)

The Confidential Unit Record Files (CURFs) of the 2004–2005 NHS contain 25,906 respondent records (19,501 adult and 6405 child records) (ABS, 2006b, NHS05 is a household survey covering 19,501 private dwellings. Non-private dwellings, such as hotels, hospitals, nursing and convalescent homes and short-stay caravan parks were not covered. Trained ABS interviewers conducted personal interviews with the selected adult member of the household, and children aged 15–17 years, with parental consent. All data provided by NHS05 is self-reported.

To allow for nationwide estimates to be obtained from the survey results, the ABS CURF attached 'weights' to each survey person. This 'weight' variable indicates the number of persons in the population represented by each person-record in the sample dataset. Application of these weights ensures that estimates will conform to an independently estimated distribution of the population by age, sex, state/territory and section of state, rather than to the distributions within the sample itself (ABS, 2006b).

The NHS05 has a particular focus on the NHPA conditions of arthritis and osteoporosis, asthma, cancer, diabetes, heart and circulatory conditions, injury and mental health, with data on arthritis, asthma, cancer, conditions of the circulatory system, diabetes and osteoporosis having in most cases been medically diagnosed (ABS, 2006a).

In late November 2009 the CURF of the 2007–2008 NHS became available. NHS08 had 20,788 participants interviewed in 15,792 private dwellings. Some of the NHS08 statistics have been used as benchmarks when validating the prototype's projections over the 2005–2010 period.

Appendix B: Australian Diabetes, Obesity and Lifestyle (AusDiab) survey

In Australia, AusDiab fills in a data gap regarding the nature and extent of the many interactions that exist between chronic diseases, including their common risk factors. It comprised a main diabetes study and a somewhat less comprehensive CVD sub-study.

Unlike the NHSs, which are cross sectional, AusDiab is a longitudinal study, it only covers adults aged 25 years or over, and it provides both self-reported and measured data. Its wave 1, in year 2000, comprised 11,247 persons, with 6500 of these attending the 2005 update (wave 2). Another 2000 of the original group (who could not attend the update) provided self-reported some of the required update information in 2005 – AusDiab has extensive data on diabetes, its risk factors, and its complications (especially CVD).

Across the 2000 and 2005 waves, for diabetes only the data from the 6537 persons who actually had physical testing (i.e., blood taken) could be used, while for CVD data from the 2000 of the original group who only provided self-reported information could be added to that 6537.

The 2000 baseline study provided benchmark national data on the number of people with diabetes, obesity, hypertension (increased blood pressure) and kidney disease. We obtained access to the baseline data set for use in this

ARC project and found that in 2000 3.63% of Australian adults aged 25 years or more had known diabetes; another 3.63% were newly diagnosed as a result of the study; people found to have 'pre-diabetes' amounted to 16% (10.4% with IGT and 5.7% with IFG); 74.9% had normal blood glucose levels; and 1.8% fell in the 'missing data' category.

The 2005 follow-up study determined how many new cases of these diseases were occurring each year, primarily as a result of people being physically inactive and eating more fat-rich foods.