Health State Transition Model by Binary Expression and Cubic Lattice Representation Corresponding to the Specific Health Checkup

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Abstract: We proposed a model that represents health checkup data in binary according to data structure of the Specific Health Checkup and visually represents the state transition of health conditions. Each of four inspection factors (body type, blood sugar, lipids, and blood pressure) were expressed as binary variable using reference values in the Specific Health Checkup, yielding 16 health condition states, (0000) through (1111). The state transition probability (256 transitions x 4 age ranges) for each of four age groups were calculated. We then constructed a health state-transition model using two cubic lattices with eight vertices. We built our models each age groups and compared these models, and could show by those how people with certain health conditions are likely to continue to change in future. Our health state transition model provides an easy visual demonstration of the health state of examinees, as well as indicating direction of the state transition.

Keywords: Metabolic syndrome, Transition model, Health states

1. INTRODUCTION

In Japan, the Specific Health Checkup program, focusing on metabolic syndrome, has been conducted since April 2008 with the goal of preventing lifestyle-related diseases [1]. Following the proposal of the Data Health Plan in 2014, the healthcare business sector in Japan was promoted under the framework of this plan, and the Specific Health Checkup and Specific Health Guidance have become the pillars of specific healthcare businesses.

We have been working on the construction of a risk assessment system based on a Bayesian network approach, which includes tests and interviews in accordance with the framework and data structure of the Specific Health Checkup [2-4]. Moreover, we have been working on the development of a sustainable health support system between medical examinations taken every other year. To provide individual health guidance to medical check-up examinees, we believed that it was necessary to clearly express the health state to which they are likely to transition in future.

To date, research on the results of medical examinations and the relationship between health guidance and the stage of behavioral change achieved, as well as research and development of tools to visually represent the transition of medical examination results using self-organizing maps or latent topic model, have been performed using the behavioral change stage model, which is one of the theoretical foundations of the

Specific Health Checkup [5-8]. While these studies are valuable to researchers, they have proved difficult for examinees to understand. Therefore, we propose a transition model that can be used to represent the health status of different examinees in various rational ways [9].

In the present study, we propose a rational method of health state representation using paired medical examination data from two consecutive years, and construct a state transition model based on the suggested causal relationship between metabolic syndrome and the health-related inspection factors tested by the Specific Health Checkup. We then show the effectiveness of our proposed model by examining the tendency for health status transition based on health checkup results, using the state transition model constructed for each age group.

2. METHOD

In this study, non-linkable anonymized health checkup data for 3,949 adult males aged 30-65 were collected from a certain medical examination center for two consecutive years. The Specific Health Checkup is a system that is applied to people over the age of 40. However, according to the Ministry of Health, Labor and Welfare, voluntary health checkups and health guidance for people under the age of 40 are effective in preventing the development of lifestyle-related diseases when they are over 40. Therefore, we also included in the analysis data for 1,474 people in 30's who underwent similar medical examinations at the same establishment.

This study protocol was approved by the ethics committee of Chubu University (approval number: 270016).

From research reports on factor analysis of conventional metabolic syndrome, the following factors are known to contribute to the development of metabolic syndrome: (1) abdominal circumference and body mass index (BMI) (body type factor), (2) fasting blood glucose and hemoglobin A1c (HbA1c) (blood glucose factor), (3) neutral fat and high-density lipoprotein (HDL) cholesterol (lipid factor), and (4) each pair of systolic and diastolic blood pressures (blood pressure factor) [10, 11]. Therefore, by taking the logical addition of the binarized test items for each factor pair and setting the bits for each factor, all test data can be expressed using the four factors of body type, blood glucose, lipid, and blood pressure. We devised a strategy to express each factor in 16 states from (0000) to (1111) and called this process 4-bit representation of “16 health states” (Figure 1).

The examinees were initially classified into one of the 16 health states based on the test data in the year they received the medical examination, and they were subsequently classified into any of the 16 states based on the test data in their medical examination from the following year. The total number of possible state transitions was thus $16 \times 16 = 256$. We classified examinees, grouped by age, into each of the 16 health states, clarified the number of state transitions among the examinees, and constructed a state transition table. We thereafter constructed a state transition probability table by calculating the state transition probability of each of the 256 transitions from this state transition table. An example list of calculated state transition probabilities for the 256 possible state transitions is shown in Table 1.

Next, as a method of visualizing the transitions of the 16 health states, we proposed a health state transition model which expresses the transitions between health states in terms of movement between the vertices of a cubic lattice.

Figure 1: An example of process 4-bit representation of “16 health states”

Table 1: An example of a list of 256 calculated state transition probabilities

	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0000	0.70	0.07	0.04	0.01	0.08	0.01	0.01	0.00	0.05	0.01	0.01	0.00	0.00	0.00	0.00	0.00
0001	0.33	0.41	0.02	0.03	0.02	0.06	0.00	0.01	0.04	0.04	0.01	0.01	0.01	0.01	0.00	0.00
0010	0.25	0.04	0.41	0.05	0.05	0.00	0.06	0.02	0.02	0.00	0.05	0.01	0.00	0.00	0.02	0.00
0011	0.10	0.15	0.15	0.27	0.04	0.02	0.02	0.05	0.02	0.00	0.01	0.10	0.00	0.01	0.00	0.05
0100	0.29	0.05	0.02	0.01	0.40	0.09	0.03	0.01	0.02	0.01	0.00	0.00	0.04	0.01	0.01	0.01
0101	0.11	0.18	0.02	0.01	0.13	0.42	0.01	0.03	0.00	0.02	0.00	0.01	0.02	0.03	0.00	0.01
0110	0.09	0.03	0.15	0.02	0.16	0.06	0.30	0.05	0.02	0.00	0.01	0.00	0.00	0.01	0.06	0.03
0111	0.01	0.09	0.07	0.04	0.04	0.18	0.13	0.24	0.00	0.00	0.00	0.01	0.00	0.03	0.01	0.13
1000	0.16	0.02	0.02	0.00	0.01	0.01	0.00	0.00	0.45	0.09	0.09	0.03	0.09	0.02	0.01	0.01
1001	0.07	0.10	0.00	0.00	0.01	0.02	0.00	0.00	0.17	0.35	0.03	0.08	0.03	0.10	0.01	0.02
1010	0.05	0.02	0.08	0.00	0.00	0.00	0.01	0.00	0.20	0.03	0.38	0.09	0.02	0.02	0.08	0.03
1011	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.07	0.17	0.17	0.32	0.01	0.05	0.04	0.10
1100	0.05	0.01	0.00	0.00	0.05	0.01	0.00	0.00	0.13	0.03	0.03	0.01	0.42	0.16	0.09	0.02
1101	0.03	0.03	0.00	0.00	0.02	0.06	0.00	0.02	0.04	0.13	0.00	0.02	0.14	0.38	0.03	0.11
1110	0.03	0.00	0.02	0.00	0.02	0.01	0.03	0.01	0.05	0.02	0.07	0.01	0.15	0.03	0.42	0.13
1111	0.01	0.01	0.00	0.01	0.02	0.03	0.02	0.04	0.03	0.05	0.03	0.11	0.04	0.14	0.11	0.34

As stated above, the number of possible health states was 16 when the four factors (i.e., body type, blood glucose, lipid, and blood pressure) of the test data were expressed in 4 bits. If we divide the 16 states in half and consider them as two sets comprising eight states each, we can express the 16 states using two cubic lattices with eight vertices. Therefore, if we consider the 256 possible state transitions as the movement between the vertices of these two cubic lattices, it becomes possible to express them with a dynamic model that is easy to understand and visualize. We called this a “health state transition model represented by a cubic lattice” and proposed it as a new method for analyzing and expressing medical examination data.

As a way to place 16 health states on 16 vertices of 2 cubic lattices, we placed 8 states with a body factor of 1 on the left cubic lattice and 8 states with a body factor of 0 on the right cubic lattice (Figure 2). Because, in the context of the Specific Health Checkup, we thought it desirable to divide the 16 states into two broad categories based on body type, with health state transitions within each body type represented by a separate cubic lattice. As a result, all the health guidance subjects selected by the layered rule of the Specific Health Checkup belong to

Figure 2: 16 health states on 16 vertices of 2 cubic lattices

the state of the left cubic lattice. Using this way of arranging health conditions, you can imagine as if there is a wall of metabolic syndrome between the left and right cubic lattices. Movement between vertices, which indicates transition between states, is indicated by an arrow, and a certain state transition probability is used as a threshold to determine whether the arrow should be displayed. In this way, we can construct a health state transition model that represents the trend of major health state transitions among examinees. In this study, we divided examinees into four age groups: 30–39 years (1,474), 40–49 years (1,934), 50–59 years (1,812), 60–65 years (203). And we constructed a health state transition model for each age group using a state transition probability of 10% as a threshold to determine the visibility of the arrows. We subsequently identified the characteristics of the models for different age groups and comparisons and examinations using them.

3. RESULTS AND DISCUSSION

3.1 The health state transition model represented by a cubic lattice

Figure 3 shows a health state transition model using data from a total of all the subjects. In this model diagram, the left cubic lattice represents the eight states of the body type factor 1 that represents overweightness/obesity, and the right cubic lattice represents the eight states of the body type factor 0 that represents healthy BMI/ideal weight. When the health state of the examinee, as measured by medical examination results, falls into cubic lattice on the left, he/she is in a state of metabolic syndrome. The (1111) state of the vertex, shown in red, represents the least favorable health outcome for the examinee, in which all four inspection factors have a value of 1 (representing the unhealthy state). Conversely, the (0000) state of the vertex, shown in blue, represents

Figure 3: The health state transition model represented by a cubic lattice using data of all subjects

the ideal health outcome, with all four factors equal to 0 (representing the healthy state). The transition probability threshold between the states indicated by the vertices of the cubic lattice is set to 0.1. The direction of state transitions whose transition probability exceeds this threshold is indicated by an arrow, with the probability value shown beside it. Blue arrows indicate improvement in health status while red arrows represent deterioration in health status, and black arrows depict stability in health status. The arrow from the left cubic lattice (body type factor 1) to the right cubic lattice (body type factor 0) indicates a break from metabolic syndrome.

Looking at the blue and red arrows in the model diagram, we notice that there are many blue arrows and can see that there is improvement trend in the case using all data. Figure 4 is a model diagram focusing on the blue arrow. All the arrows in the figure show improvement of health condition, but the routes that go from the cubic lattice on the left to the cubic lattice on the right and go beyond the wall of the metabolic syndrome are two routes of (1000)→(0000) and (1001)→(0001). It turns out that the state transitions from bad health with many 1s in four factor bits [for example, the (1111) state or the (1110) state] to good health beyond the wall of metabolic syndrome are unlikely. On the other hand, Figure 5 is a model diagram focusing on the red arrow. These arrows

Figure 4: The model diagram focusing on the blue arrow

Figure 5: The model diagram focusing on the red arrow

in this figure all indicate the deterioration of the health condition, but there is only one route $(0111) \rightarrow (1111)$ that worsens beyond the wall of metabolic syndrome. Contrary to the previous case, it can be seen that it is unlikely that the state of health will deteriorate beyond the wall of metabolic syndrome from the state where there are many 0s in four factors bits [for example, (0000) or (0001)]. From the above, it just tends to occur that the transitions across the left and right cubic lattices which indicates whether or not the metabolic syndrome when all factors other than the body type factor have improved/deteriorated (condition where bit values aligned by 1 or 0). This is considered to indicate the priority of the body type factor compared with other factors, and we think this finding that support the superiority of abdominal circumference and BMI in the stratification procedure of the Specific Health Checkup.

Also, in any of the 16 states, the black arrow that stays in the same state shows the highest probability, and the number of blue arrows is larger than the red arrows, so that as tendency of the all subjects, the health conditions tend to stay the same state, but the state transitions toward improvement tend to occur when the state changes. From this, it shows that there is sufficient potential for health states to be maintained or improved by health guidance following a medical examination. Furthermore, since most of the blue and red arrows in the model diagram are on the edges of the lattice, when it occurs change of health, we understand that there are many changes in state that changes only one bit in the four factor bits. We consider this shows that it is more likely to change the condition by the improvement of one factor than improvements of multiple factors of the four factors of metabolic syndrome. Therefore, in the field of health guidance, it is desirable to provide guidance with the aim of improving the problematic metabolic syndrome factors one by one, and ultimately aim at reaching the (0000) state.

3.2 The characteristics and comparisons of the models for different age groups

The health state transition model diagrams of each age group are shown as examples in Figure 6 and Figure 9, respectively.

Figure 6 is the model diagram of the health transition of the 30–39 years age group. Looking at this figure, the only arrow crossing the left and right cubic lattices which indicates a break from metabolic syndrome is $(1000) \rightarrow (0000)$. In the 30s of the subjects they need to have all three factors other than body type within the reference range (three bits show 0) before break from

Figure 6: The health transition model for the 30–39 years age group

Figure 7: The health transition model for the 40–49 years age group

metabolic syndrome. The other blue arrows indicate the transitions starting from the state where the factors other than the body type factor are 1 and improving it to 0. The two states of (1000) and (1010) are overlapped by the blue and red arrows, indicating that improvement or worsening occurs between these two states.

In the health state transition model for the 40–49 years age group, as shown in Figure 7, examinees demonstrated a high probability of improving to a more favorable health condition when only one factor, other than body type, exceeded the reference range. In addition, the model contains only one arrow that crosses the left and right cubic lattices from the (1000) state to the (0000) state. This implies that the transition out of metabolic syndrome requires that all three factors other than body type fall within the reference range prior to transition.

In the model diagram of the 50–59 years age group shown in Figure 8, the route of $(1000) \rightarrow (0000)$ which is the same as those in their 30s and 40s, is seen the only route for break from metabolic syndrome. However, the overlap of blue and red arrows, which was few in the 30s and 40s, increase in the model diagram of this group, and the difference that one factor other than body shape is likely to improve or worsen is seen.

Figure 8: The health transition model for the 50-59 years age group

Figure 9: The health transition model for the 60-65 years age group

In the 60-65 years age group shown in Figure 9, blue arrows and red arrows overlapped frequently, and bidirectional switching between states occurred randomly. So, there is no characteristic tendency. Moreover, since there are no arrows that cross the left and right cubic lattices, it seems that it is not easy for people in their 60s to break from metabolic syndrome.

Up to this point, we have seen the state transition model of each age group in Figures 6-9. In all age groups, all state transition arrows except for the arrow that crosses between the left and right cubic lattices occurred on the edge of the left or right lattice, and no transitions [for example, (1101) state $\rightarrow$ (1000) state] were seen deviating from each lattice edge. In the criterion of transition probability threshold of 0.1 indicates that there is only one factor state transition occurs.

In addition, the increase in the overlapping of blue and red arrows, which became noticeable in the model diagrams of the 50s and 60s, shows that between these conditions, the examinees healthy condition can easily change from a favorable condition to an unhealthy condition or vice. This suggests that there is a need for continuous health guidance for people in this age bracket to help them maintain their good health, and, after

an improvement has been observed, to avoid health deterioration in the future. Then, we created a health state transition model diagram using the data in the 30s that we added to the trial in this study, and compared it with the model of other age groups, and we found as a result there was not a significantly different from the model diagram of the 40s. This is a result that can be considered to indicate that persons in their thirties need the same medical examination and guidance as those in their forties. On the other hand, it is a result that can be considered as showing that even if they were in their 40s, they would be in time even if they didn't hurry to give health guidance from their 30s.

3.3 The main route for improving health conditions

Our proposed health state transition model represented by a cubic lattice can also show what kind of change in the state of health a person in a certain state is likely to undergo in the future. Figures 10 and 11 show the main routes from the (1111) state. The thick arrows in these figure indicate the state transition with the highest probability from each states and the thin arrows show other state transitions. We show in Figure 10 what kind of health conditions the 40s examinees in the (1111) state will follow. This figure shows that examinees in

Figure 10: The main routes of 40s examinees from the (1111) state will follow

Figure 11: The main routes of 60s examinees from the (1111) state will follow

their 40s in the (1111) state can easily follow the route of $(1111) \rightarrow (1011) \rightarrow (1010) \rightarrow (1000) \rightarrow (0000)$. This shows that we can expect to improve from the unhealthiest state (1111) to the healthiest state (0000). In other words, by giving appropriate health guidance to people with metabolic syndrome in their 40s who are in poor health, their health status can be improved to a state of no problem in a few years. On the other hand, the main state transition routes of the 60s examinees in the (1111) state shown in Figure 11 are only $(1111) \Leftrightarrow (1101)$. This indicates that one-way improvement in health status cannot be expected for the 60s examinees in the (1111) state. Therefore, it is considered necessary for the examinees in their 60s (1111) state to work on health guidance assuming a route that complicates state transitions with a small probability (less than 0.1) not shown in Figure 11. We think that it is necessary to patiently work on the health improvement guidance that goes back and forth, because even if their health conditions are improved by health guidance, they return to their original bad state if they are careless.

4. CONCLUSION

In the present study, we proposed the health state transition model represented by a cubic lattice. Based on the opinion of the Ministry of Health, Labor and Welfare, we also added data for people in their 30s who are not subject to the Specific Health Checkup to the data to be analyzed and conducted a comparative study. We constructed the health state transition model represented by a cubic lattice for each age group analyzed in the study, performed a comparison between these models, and demonstrated that models of this type provide a useful and easily understandable method of visualizing and predicting health state transitions. The health state transition model represented by a cubic lattice can be used as a convenient visual indicator of the current health status of examinees, as well as indicating the direction probability of future health state transitions. We thus believe it to be a promising model for health state transition analysis. It is expected that the health state transition model and health guidance based on the results of this analysis, as well as awareness of the age-related and health state trends depicted by these models, will lead to efficient and effective health maintenance and improvement. In the future, we plan to conduct a field test of the health state transition model represented by a cubic lattice and examine its usefulness in actual health guidance.

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