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A hardware-based asthma simulator based on ergodic cellular automaton dynamics

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Abstract— Lipopolysaccharides (LPS), which exist in the air and other environments, act as endotoxins and are known to induce three different immune responses: Th1, Th2, and Th17, depending on the amount of LPS ingested. If the immune balance between Th1 and Th2 cells is disrupted, with Th2 cells becoming excessive, allergy symptoms and asthma can occur. Th17 is also known to be involved in the development of severe asthma. In this study, we present an ergodic cellular automaton asthma simulator for simulating a mathematical model that switches between the three Th phenotypes (Th1, Th2, and Th17) in response to various amounts of LPS. We also implemented the presented model and an ordinary differential equation asthma model on an FPGA and made comparisons. The comparison results showed that the presented model required fewer circuit components and reduced power consumption compared to the differential equation model.

1. Introduction

The immune system protects our bodies from various pathogens, where different types of T helper cells (Th cells) work as command centers of the immune system for different types of pathogens. The Th cells are differentiated from the naive T cell depending on interactions among the pathogens (i.e., input to the immune system) and biologically active substances (i.e., internal states of the immune system). However, overproduction of the Th cell sometimes causes allergies. On the other hand, recently, various biological system simulators based on nonlinear dynamics of ergodic cellular automaton (CA) have been developed [1], where their advantages include consumption of much fewer hardware resources and much lower power compared to digital-processor-based biological system simulators. Based on the above backgrounds of the asthma simulator and the ergodic CA biological system simulators, in this paper, a novel hardware-efficient ergodic CA asthma model is presented [2].

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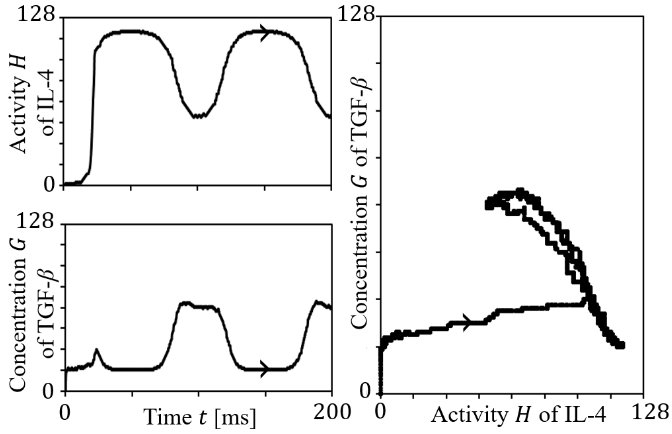

Figure 1: Waveforms of a novel hardware-efficient asthma model based on an ergodic cellular automaton (CA).

2. Ergodic cellular automaton asthma model

The asthma model using ergodic cellular automata has four registers that store the discrete state variables H and G and the discrete auxiliary variables P and Q. These variables are defined by the following Eq. (1).

$$\begin{aligned} &H \in Z_N = \{0, \ldots, N-1\}, G \in Z_N, \\ &P \in Z_M = \{0, \ldots, M-1\}, Q \in Z_M. \end{aligned} \tag{1}$$

The presented model receives the periodic clock $C(t)$ and switch signals S_H, S_G as shown below. $C(t) = \sum_{n=0}^{\infty} p(t - nT)$, $S_H(t) = \sum_{n=0}^{\infty} q(t - nT_H - \Phi_H, W_H)$ (S_G is defined similarly). $q(t, W)$ is the instantaneous pulse with $q(t, W) = 1$ when $t \notin [0, W]$ and $q(t) = 0$ when $t \in [0, W]$, where T is the period. When $C(t) = 1$, H and G undergo the state transitions in Eq. (2).

$$\begin{aligned} H(t^+) &= H(t) + S_H(t)\mathcal{F}_H(H(t), G(t), P(t)), \\ G(t^+) &= G(t) + S_G(t)\mathcal{F}_G(H(t), G(t), Q(t)), \end{aligned} \tag{2}$$

where, $\mathcal{F}_H \in \{-1, 0, 1\}$ and $\mathcal{F}_G \in \{-1, 0, 1\}$ are discrete functions. Fig. 2 shows the time waveform of the presented model and the increase or decrease of H (IL-4) with respect to the LPS injection level. These phenomena simulate those of the mathematical model [3].

3. Conclusions

Comparisons showed that the presented model was much more hardware-efficient (i.e., consumes much fewer circuit elements and lower power) compared to the ODE asthma model [3]. Therefore, the results of this paper will contribute to developing hardware-efficient immune system simulators (including asthma simulator) for personalized drug discovery and medicine. This research was supported by JSPS Grant-in-Aid for Scientific Research 21H03515.

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