Signal Transmission Through Human Body via Human Oxygen Saturation Detection

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Abstract. For a long time, people have carried out various studies on molecular communication and nano information network in order to realize biomedical applications inside human body. However, how to realize the communication between these applications and the outside body has become a new problem. In general, different components in the blood have different absorption rates of the different light. Based on this, we propose a new through-body communication method. The nanomachine in the blood vessel transmits signal by releasing certain substances which can influence blood oxygen saturation. The change of blood oxygen saturation can be detected by a outside body device measuring the attenuation of different light through blood. The framework of the entire communication system is proposed and mathematically modeled. Its error performance is discussed and evaluated. This research will contribute to the realization of the connection of communication systems inside and outside the human body.

Keywords: molecular communication · nanomachine · oxygen saturation · light absorption

1 Introduction

In recent years, molecular communication has become a research hotspot because nanomachine is expected to use in actual test. It is possible for us to use nanomachine to form the internet of nano things and complete the communication inside and outside the human body [1]. So far, the problem of designing a suitable interface between the nanoscale environment and the external macroscopic world remains an open research issue.

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There are many studies on the theoretical research of communication systems inside and outside the human body such as [2,3]. In [2], the authors set up nanomachines in the human body and send signals by stimulating nerve fibers through electrodes. This signal propagates through the nerves and produces a surface electromyography signal, which serves as the information received by the body surface receiver. However, the signal transmission through the nervous system is susceptible to the interference of the action caused by the subjective consciousness of the human body on the neural signal reception. In literature [3], the authors used blood vessels as communication channels and used smart probes fixed in them as a tool for information interaction inside and outside the human body. The probes are expected to release a substance that generates an allergic reaction on the skin surface, or is detectable in the infrared bandwidth or by ultrasound. However, the authors did not elaborate on how to implement these ideas.

We notice that the oximeter is often used outside human body to detect the blood oxygen saturation in blood vessels. We can utilize this technique to realize the communication system through human body. Blood oxygen saturation is one of the important basic data in clinical medicine, which can be inferred by measuring the attenuation of different light through blood. The signal transmission through the body can be achieved by altering blood oxygen saturation and detecting its change outside human body by optical method.

The main contributions of this paper are:

1) We propose a new through-body communication method that people can make use of blood oxygen saturation detection as a medium for information interaction inside and outside the human body. The framework of the entire communication system is proposed.
2) Our proposed system is mathematically modeled and the error performance is evaluated.

The rest of this paper is organized as follows. Section 2 introduces preliminary knowledge of optical technology and oxygen saturation, and the design of through-body communication system. Section 3 presents the mathematical model of our system. Section 4 presents the simulation results. Section 5 concludes the paper.

2 Design of Through-Body Communication System

In this section, we will make a further explanation about blood oxygen saturation and the principle of optical detection in this process. After that, we will introduce the design of our communication system with blood oxygen saturation detection as a medium for information interaction.

2.1 Blood Oxygen Saturation

The oxygen consumed by the human body mainly comes from the oxygen carried by hemoglobin. There are four kinds of hemoglobin in normal blood: oxygenated hemoglobin (HbO_2), deoxyhemoglobin (Hb), carboxyhemoglobin (COHb) and Methemoglobin (MetHb). In fact, both MetHb and COHb absorb red and infrared light. This will result in incorrect readings. MetHb is less than 2% and COHb is less than 3% of the total amount of hemoglobin in normal human body. Among them, deoxyhemoglobin is reversibly combined with oxygen, while carboxyhemoglobin and methemoglobin are not combined with oxygen. The blood oxygen saturation (S_{O_2}) is used to describe the change of oxygen content in blood. It refers to the percentage of bound oxygen volume in total blood volume. The function of hemoglobin is to carry oxygen to all parts of the body. The oxygen content of hemoglobin at any time is called blood oxygen saturation. It can be expressed as

$$S_{O_2} = C_{HbO_2}/(C_{HbO_2} + C_{Hb}).$$

As for the oxyhemoglobin dissociation curve, also called the oxygen dissociation curve (ODC), is a curve that plots the proportion of hemoglobin in its saturated (oxygen-laden) form on the vertical axis against the prevailing oxygen tension on the horizontal axis. This curve is an important tool for understanding how our blood carries and releases oxygen. Specifically, the oxyhemoglobin dissociation curve relates oxygen saturation (S_{O_2}) and partial pressure of oxygen in the blood (P_{O_2}) [4].

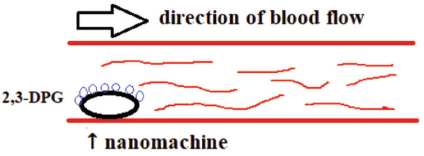
2.2 Principle of Optical Detection

As we mentioned before, hemoglobin has both oxygen carrying state and no-load state. Hemoglobin in carrying oxygen state is called oxyhemoglobin, and hemoglobin in no-load state is called deoxyhemoglobin. Oxyhemoglobin and deoxyhemoglobin have different absorption characteristics in the spectrum range of visible light and near infrared. Deoxyhemoglobin absorbs more red frequency light and less infrared frequency light. Oxyhemoglobin absorbs less red frequency light and more infrared frequency light. The principle of a fingertip pulse oximeter is based on this fact. When red light and infrared light irradiate the finger alternately, the photodiode in the fingertip pulse oximeter will produce a weak photocurrent that changes with the pulse. After converting, filtering and amplifying the photocurrent, the pulse waveform is obtained. The pulse frequency is calculated from the peak spacing, and the blood oxygen saturation is calculated from the photocurrent ratio of red light and infrared light.

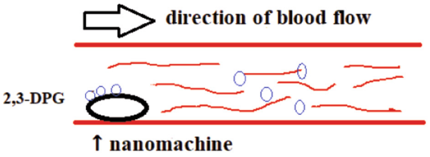
According to literature [5], when light of a specific wavelength is incident on the fingertip, the transmitted light intensity can be divided into two parts: the pulsatile component and the non-pulsatile component in the fingertip tissue. When the arterial blood vessels in the light-transmitting area pulsate, the amount of light absorbed by the arterial blood will change accordingly, which is called current (AC) component. The absorption of light by other tissues such as skin, muscle, bone and venous blood is constant and is called direct current (DC) component. If the attenuation due to factors such as scattering and reflection is ignored and according to the Lambert-Beer law, when the wavelength is λ and the monochromatic light with the light intensity of I_0 is vertically incident, the transmitted light intensity can be written as

$$I = I_0 e^{-\varepsilon_0 C_0 L} e^{-\varepsilon_{HbO_2} C_{HbO_2} L} e^{-\varepsilon_{Hb} C_{Hb} L}, \tag{1}$$

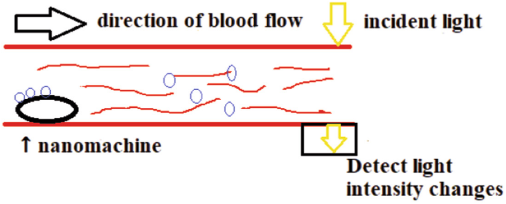
where ε_0, C_0, L are the absorption coefficient, the concentration of light absorbing substances and the optical path length of non-arterial components in the tissue and venous blood. C_{HbO_2}, ε_{HbO_2} are the absorption concentration and coefficient of HbO_2 in arterial blood. C_{Hb} and ε_{Hb} are the absorption concentration and coefficient of Hb in arterial blood.



(a) Set the nanomachine in human body



(b) Nanomachine releases 2,3-DPG



(c) Detect light intensity changes

Fig. 1. The data transmission via human oxygen saturation detection.

2.3 System Design

In order to achieve a feasible change of blood oxygen saturation in blood vessel and make decisions based on the received light intensity at the receiving end, we need to release something to change the affinity of hemoglobin for oxygen. According to the literature [6], CO_2 concentration, pH value, temperature and

2,3 diphosphate glyceride (2,3-DPG) all affect the affinity of hemoglobin for oxygen, thus causing changes in blood oxygen saturation. For safety and practical considerations, the pH value and temperature in human blood vessels cannot be easily changed, and CO_2 is unable to be carried by nanomachine as a gas molecule, so we consider that 2,3-DPG is used to change blood oxygen saturation. Under the condition of other situations are the same, the oxyhemoglobin dissociation curve shifts to the right with the increase of 2,3-DPG [6], which also represents the decrease in blood oxygen saturation. We assume that the blood oxygen saturation variation caused by 2,3-DPG variation is much faster than that that of regular natural saturation changes. The basic idea of our system design is that nanomachine releases 2,3-DPG to change the blood oxygen concentration, thereby producing a change in the light intensity at the receiving end and realizing the acceptance judgment. The whole process is shown in Fig. 1.

3 Mathematical Modeling of Communication System

In this section, the mathematical modeling of the entire communication process from the nanomachine in human body to the outside-body processing unit are presented.

The general idea is that 1) setting the nanomachine on the upstream of human fingertips so that the nanomachine can release the 2,3-DPG when they need to send signal, and 2) using a device which make an optical measurement of blood oxygen saturation on the downstream of human fingertips. In this way, the data transmission from the nanomachine to the outside body device can be realized.

If the nanomachine transmits a bit $x \epsilon \{0, 1\}$ to the outside of the human body, the nanomachine will release a certain amount of 2,3-DPG, which may be set as M molecules, then the released 2,3-DPG concentration $A(t)$ can be defined as

$$A(t) = \begin{cases} M, & x = 1 \\ 0, & x = 0 \end{cases} \tag{2}$$

Next, in order to simplify the problem,we assume that 2,3-DPG molecules first move under blood flow and then react with hemoglobin to reduce blood oxygen saturation. The diameter of 2,3-DPG molecule is much less than the diameter of the transverse palmar branch since the volume of 2,3-DPG is around 10^{-19} mm^3 and the diameter of the transverse palmar branch is around 0.4 mm [7]. In the case of limited transmission distance, we can regard the process of 2,3-DPG molecular transmission in fingertip vessels as a borderless system. We adopt a model in [8] for 3-D advection-diffusion where the 2,3-DPG concentration at time t is presented as

$$C(t) = \frac{M}{(4\pi Dt)^{3/2}} e^{-\frac{(d-vt)^2}{4Dt}}, \tag{3}$$

where v is the speed of blood flow, and d is the distance between nanomachine and the receiver. D is the diffusion coefficient for 2,3-DPG molecules in blood vessel.

The sensing of molecular concentration occurs within a spherical receptive space with volume V. Additive counting noise is generated due to the random motion of the information molecules. From [9], the total noisy molecule concentration Z(t) is given by

$$Z(t) = C(t) + n(t), \tag{4}$$

where $n(t)$ is the non-stationary and signal dependent additive noise. When 2,3-DPG molecules arrive at the receiver area, the blood oxygen saturation S_s can be expressed as

$$S_s = (C_{HbO_2} - f(M,t))/(C_{HbO_2} + C_{Hb}). \tag{5}$$

where $f(M,t)$ is the function which represents the decrease part in HbO_2 concentration after the release of 2,3-DPG.

Reference [6] gives a clear derivation of the relationship between the 2,3-DPG and S_{O_2}, which is too complex. We obtain another way to calculate it approximately. We adopt a model in [10] to calculate oxygen saturation. Its equation for the ODC describes the oxygen saturation S_{O_2} as a function of oxygen partial pressure P_{O_2} relative to the half-saturation level P_{50}

$$S_{O_2} = (P_{O_2}/P_{50})^n/[1 + (P_{O_2}/P_{50})^n], \tag{6}$$

where n is the Hill exponent. The value n = 2.7 was found to fit well to the data for normal human blood in the saturation range of 20–98%. According to [6], when pH = 7.24, P_{CO_2}= 40 mmHg, T=37°C, the relationship between P_{50} and C can be calculated as

$$P_{50} = 26.8 + 795.63(C - 0.00465) - 19660.89(C - 0.00465)^2. \tag{7}$$

From literature [11], P_{O_2} in arterial blood is around 90 mmHg. Thus, we can calculate the relationship between the 2,3-DPG and S_{O_2} to choose the best 2,3-DPG concentration based on (6) and (7).

The output decoding can also be performed according to the general method of oximeter measurement. Two beams of light with different wavelengths (red light and infrared light) are used as the incident light in the measurement of blood oxygen saturation. When the wavelength of the infrared light is taken near 805nm, the blood oxygen saturation can be expressed as

$$S_{O_2} = A * \frac{I_{AC}^{\lambda_1}/I_{DC}^{\lambda_1}}{I_{AC}^{\lambda_2}/I_{DC}^{\lambda_2}} - B, \tag{8}$$

where A, B are expressions about the absorption coefficient, which can generally be regarded as constants. $I_{AC}^{\lambda_1}$, $I_{AC}^{\lambda_2}$ are respectively the pulsatile component of transmitted light intensity when the light with a wavelength of λ_1 or λ_2 vertically enters the arterial blood of the fingertip of the human body. $I_{DC}^{\lambda_1}$,

$I_{DC}^{\lambda_2}$ are respectively the non-pulsatile component of transmitted light intensity when the light with a wavelength of λ_1 or λ_2 vertically enters the venous blood of the fingertip of the human body. In this way, we can detect the oxygen saturation at the receiver as S_r. The decision equation of the receiver is

$$\hat{x} = \begin{cases} bit"1", \ S_r \leq S_{th} \\ bit"0", \ S_r > S_{th}, \end{cases} \tag{9}$$

where S_{th} is the receiver's decision threshold and $\hat{x}$ is recovered signal.

4 Stimulation Results

In this section, the error rate of the through-body communication system is evaluated by MATLAB. The distance between nanomachine and receiver is chosen from 8 mm to 12 mm since the distance between the middle transverse palmar branch and the distal transverse palmar branch is about 10.33 mm [7]. Considering that the reasonable range of the blood flow velocity is from 30 mm/s to 126 mm/s [12], we set the velocity from 30 mm/s to 50 mm/s. We assume that the diffusion coefficient D is 200 mm^2/s in blood vessel. We define M in (3) is 50000. From (4) and (5), we can know the received number of 2,3-DPG is directly related to blood oxygen saturation. In order to simplify the simulation calculation process, we define the threshold of molecule number M_{th} is 8. We send 100,000 bits of data in a simulation and the number of molecules received is counted and judged by a spherical receiver with a volume of 1 mm^3. What's more, for the probabilities of sending bit "1" and bit "0" at the nanomachine, we choose 0.5 for both of them.

Considering that there may be 2,3-DPG that cannot be cleared in time and remain in the blood vessel, we add the inter-symbol interference (ISI) influence and additive noise. We assume that ISI effect can last for eight time slots. Every time slots lasts $t = d/v$ since the concentration of 2,3-DPG becomes maximum at this time. Besides, we add gaussian white noise with a signal-to-noise ratio of 20dB in the channel. Both the signal of current time slot and the legacy signals of the previous eight time slots are disturbed by additive noise. Table 1 shows some important parameters used in the simulation.

Table 1. Stimulation parameters

Parameter	Symbol	Value
Distance between nanomachine and receiver	d	8 mm to 12 mm
Blood flow velocity	v	30 mm/s to 50 mm/s
Diffusion coefficient	D	200 mm^2/s
Number of 2,3-DPG molecules	M	50000
Volume of the receiver	V	1 mm^3

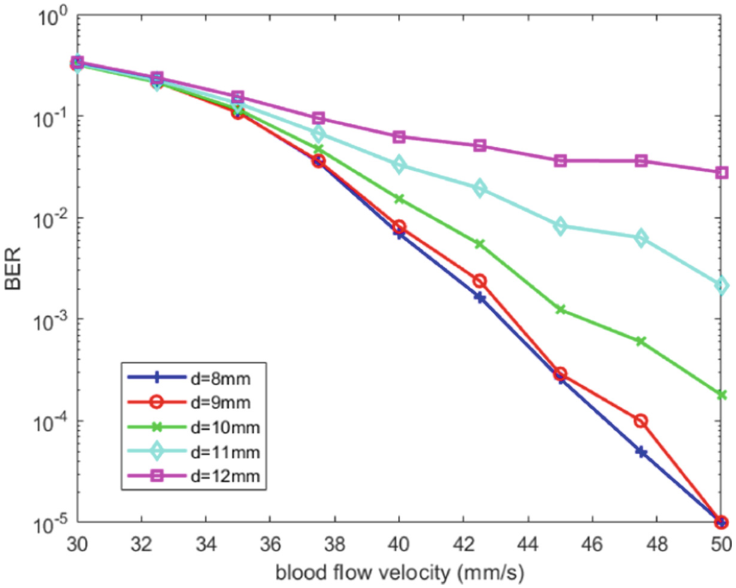


Fig. 2. The relationship of BER and blood flow velocity for different distances between nanomachine and receiver.

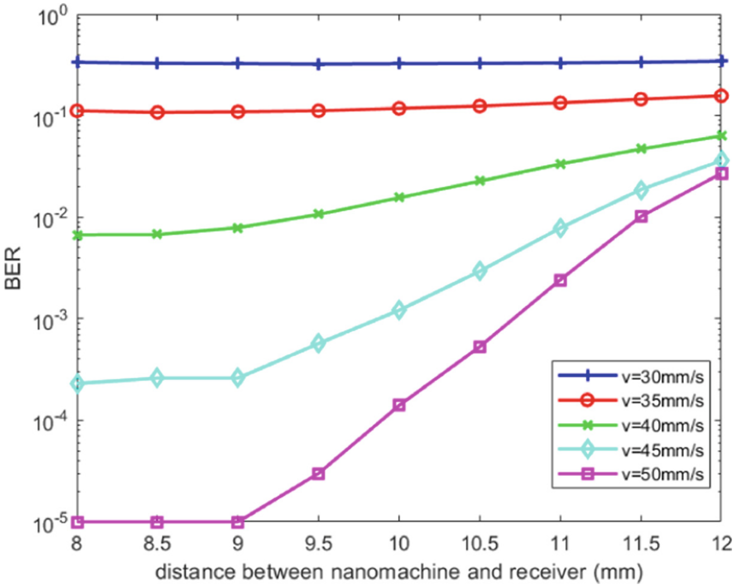


Fig. 3. The relationship of the BER and the distance between transmitter nanomachine and the receiver for different blood flow velocities.

The relationship of bit error rate (BER), blood flow velocity is shown in Fig. 2. It can be seen that as the increase of v, the BER decreases. This is because the increase of v leads to a larger peak value in (3). It also speed up the concentration decay to reduce the influence of the long tail effect of signal molecules when 2,3-DPG molecules diffuse. Therefore, ISI is reduced in this process and more molecules will be received at the receiver.

It can also be seen that as the increase of d, BER decreases in Fig. 3. Similar to the discussion process for v, the increase of d leads to smaller peak value $C(t)$, and further less 2,3-DPG molecules arriving at the receiver.

5 Conclusion

In this paper, we propose a new communication system between nano information network inside human body and external network. The transmitter nanomachine in the blood vessel sends signals by releasing 2,3-DPG to alter the blood oxygen saturation. The outside receiver detects the blood oxygen saturation by optical technology to make decision. The framework of the whole communication system are presented and mathematically modeled. The influence of blood flow velocity and the transmitter receiver distance on the BER are simulated and discussed. In our future work, we will focus on the study of the channel capacity of our proposed system.

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