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Review article

Applications of molecular communications to medicine: A survey

L. Felicetti[a], M. Femminella[a], G. Reali[a,*], P. Liò[b]

[a] *Department of Engineering, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy*

[b] *Computer Laboratory, University of Cambridge, 15 JJ Thomson Avenue, Cambridge CB3 0FD, UK*

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ABSTRACT

In recent years, progresses in nanotechnology have established the foundations for implementing nanomachines capable of carrying out simple but significant tasks. Under this stimulus, researchers have been proposing various solutions for realizing nanoscale communications, considering both electromagnetic and biological communications. Their aim is to extend the capabilities of nanodevices, so as to enable the execution of more complex tasks by means of mutual coordination, achievable through communications. However, although most of these proposals show how devices can communicate at the nanoscales, they leave in the background specific applications of these new technologies. Thus, this paper shows an overview of the actual and potential applications that can rely on a specific class of such communications techniques, commonly referred to as molecular communications. In particular, we focus on health-related applications. This decision is due to the rapidly increasing interests of research communities and companies to minimally invasive, biocompatible, and targeted health-care solutions. Molecular communication techniques have actually the potentials of becoming the main technology for implementing advanced medical solution. Hence, in this paper we provide a taxonomy of potential applications, illustrate them in some detail, along with the existing open challenges for them to be actually deployed, and draw future perspectives.

Contents

* Corresponding author. Tel.: +39 075 585 3651; fax: +39 075 585 3654.
E-mail addresses: ing.luca.felicetti@gmail.com (L. Felicetti), mauro.femminella@unipg.it (M. Femminella), gianluca.reali@unipg.it (G. Reali), pl219@cam.ac.uk (P. Liò).

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1. Introduction

In recent years, nanoscale communications have inspired a huge research effort in many fields [1–3], including medical science [4,5], environmental control, and material science. Research activities have focused on different types of nanomachines, from those based on carbon nanotubes and carbon nanowires [6] to biological ones [7,8]. Due to the heterogeneity of environments and communication techniques exploitable at the nanoscales, it is unfeasible to identify general models, valid for most of nano-communication technologies [9], such as terahertz communications [10], neuronal communications [11], and molecular communications [12]. In fact, context and micro-environmental features have a deep influence on the models of each communication scenario. For this reason, an extensive literature relevant to the analysis of different innovative communication solutions at the nanoscales exists.

Molecular communications have received a lot of attention since they are considered an alternative approach to electromagnetic communications due to their unique features of biocompatibility and minimal invasiveness, which are essential for them to be used in living bodies. This class of communications takes inspiration from some existing communication mechanisms between biological entities. It consists of using relatively small molecules, such as hormones and other small proteins (e.g. cytokines), peptides, carbohydrates, lipids and combinations of them, which can propagate from a transmitter to receivers. The response of such communicating biological entities (i.e. natural and/or artificial cells) is highly specialized. Indeed, receivers must recognize different signals associated with different molecules received through their specialized membrane receptors. Actually, the cell membrane may contain hundreds or thousands of receptor molecules for each type of compatible ligand. Depending on the signals (i.e. types of molecules) received by a cell, different behaviors are triggered [13]. By exploiting these communication mechanisms, the ongoing research on molecular communications is highly oriented to expanding capabilities of nanodevices, by enabling the execution of complex tasks through their coordination. However, many proposals are essentially focused on design and analysis of communications techniques and protocols at the nanoscales, often without a sound analysis of the wide set of applications that can benefit from these proposals. The essential contribution of this works is to identify and classify the applications that can benefit from nanoscale molecular communications in the medical field. A contribution on this subject can be found in [4], although at a very early stage. It is also worth to mention the paper [14], which is a survey of nanotechnology applications for health care, but it does not include any discussion on the potential applications and benefits achievable by the introduction of molecular communications. Hence, this survey contributes to organize and classify the medical scenarios that are believed to significantly benefit from this kind of communications. Although full-fledged artificial biological nanomachines are far from being considered ready for systematic production and exploitation [15], biochemists have achieved significant milestones, such as the creation of cell components, such as artificial ribosomes, which can be used for the artificial synthesis of proteins [7,8]. In addition, the theoretical and computational models of biological circuits enabling molecular communication have already been assessed [16].

Some realistic results achievable in the mid-term consist of emulating nanoscale biological processes through computational intensive simulation platforms [17]. This way, it is possible to realize personalized predictions of the evolution/trajectories of diseases, starting from a limited number of biomarkers,[1] without the need of executing the traditional in-vivo tests on patients [18,19]. The computational models are based on a detailed characterization of the molecular communication parameters done by using results of in-vitro and in-vivo experiments. The key aspect of this approach is translating general experimental results in numerical functions that can be parameterized through marker values relevant to each individual patient, so as to produce a personalized medical characterization of a patient, including risk assessments, thus helping medical personnel to identify optimal treatments.

An example of longer-term objectives of nanoscale communications consist of designing and implementing nano-sensors and nano-actuators for the prevention, detection, and treatment of a large set of diseases, such as cardiovascular diseases or tumors. For instance, specific proteins can be delivered for activating the immune system and/or triggering drug delivery systems in small

[1] A biomarker is a traceable substance that is introduced into an organism as a means to analyze some health-related aspects, or a substance whose detection indicates a particular disease state. In this work, we will refer to biomarkers as the second definition. Specifically, a biomarker indicates a change in expression or state of a protein that correlates with the risk or progression of a disease, or with the susceptibility of the disease to a given treatment.