Exploring current and future technologies to make sense of the biophoton phenomenon: a narrative review

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Abstract

Biophotons is the very weak light generated by cells. This light has been shown to change with different states of cell activity and/or cell health. Although their precise significance is still not clear, biophotons are thought to function as a means of cell-to-cell communication and cell repair. In this narrative review, we consider first, the current technology available that detects biophotons. These include (1) photomultipliers: these devices have advantages of giving real-time outputs, cover a relatively large detection area and have a low dark-noise per unit detection ability; their quantum efficiency is not great however and they do not have the ability to capture images; (2) image detectors: can capture images with an ultra-sensitive camera, together with count photons from living tissue; their process of acquiring an image can take a long time however, and their photon counts are less accurate than those obtained with photomultipliers and (3) histological methods: that relies on the reduction of silver $(Ag)^{+}$ to Ag that is thought to mark sites of photon activation and can be identified with a light microscope; there are however, some issues on how this reduction process affects the tissue and whether it can influence biophoton count. Next, we consider prospects for future methods that may determine both the functional significance of biophotons, together with how their detection can be used clinically. The development of better technology in the field of biophoton research can reveal a better understanding of how the brain functions under both normal and pathological conditions.

Key words: electron multiplying charge coupled device; *in situ* biophoton autography; photomultipliers; ultra-weak photon emission

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Introduction

Many, if not all, cells in our bodies have the ability to respond to light. This includes not only cells that are located superficially in the body and are exposed directly to light, but also those located very deep and are not normally exposed to light. Although it remains a mystery as to why these deep lying cells – that normally work in complete darkness – have a response to light, one rather intriguing explanation is based on the concept that all living cells can not only respond to light, but they can generate light as well. That they emit light extensively as part of their normal day-to-day functioning. This concept has been referred to as ultra-weak photon emissions or more recently, biophotons.[1-5]

Previous studies have reported two rather striking features of the biophoton emissions; (1) they may include a broad range of wavelengths, from ultraviolet to infrared and (2) their intensity can vary considerably. Both these features can change dramatically and they appear dependent on the different states of activity and/or health of the cell.[1-5]

Although their precise significance is not clear, biophotons have been considered to reflect variations in oxidative metabolism and to function as a means of cell-to-cell communication and cell repair.[1-5]

However, as with so many fields of neuroscience, the advancement of knowledge into the significance of biophotons has been limited by the technology available.

In this narrative review, we discuss what we consider to be some of the key technologies required to make some sense of the biophoton phenomenon, together with its functional significance. These technologies include particular devices that measure; first, the light itself and its patterns of intensity (i.e., the emissions) and second, the different wavelengths involved. Next, we explore the future prospects of biophoton research, how to determine their precise functional significance, how to better define their activity in the whole organism and how they can be used as a clinical tool in the living brain (i.e., their use to detect and treat medical ailments). These will be considered in turn below. First, an introduction to the biophoton concept and its implications will be considered.

Search Strategy

Electronic searches of the pubmed database for literature with the key words "biophotons," "ultra-weak emissions," "photomultiplier," "electron multiplying charge coupled device" or "*in situ* biophoton autography" were performed. The results were further screened by title and abstract to include articles on animals, humans and cell culture that were directly relevant to these key search items. The search included publications up to and prior to July 2024. The articles that were not specific for the key words nor directly relevant to the issues considered in this review, were not included.

The Biophoton Phenomenon

In the sections that follow, we explore some of the key issues associated with the biophoton phenomenon.

Where do biophotons come from?

Biophotons are thought to arise through cellular metabolism. During this process, as molecules move from high to lower energy states, electrically excited products are generated, together with light. The main players involved are small organelles called mitochondria, the so-called "engine rooms" of cells. Mitochondria produce the vital energy (adenosine triphosphate [ATP]) that drives so many intrinsic cells functions, together with maintaining the critical balance, the ebb and flow, of reactive oxygen species (ROS) within the cell (**Figure 1**).[2-5] Because most of the mitochondria are within the cell itself, the biophoton signal has been suggested to be stronger inside the cell, than just outside it.[6] Microtubules are also suspected to play a key role in the intracellular transmission of biophotons. These organelles are well-known to form a "railroad network" for macromolecular transport, together with providing mechanical support for the positioning of organelles; through this transport network, microtubulues are thought to capture and transmit biophotons along the neurone and to facillitate a change in functional activity.[2, 3, 7, 8]

Real or fake? Are biophotons doing something useful?

For three key reasons, the biophoton emissions have been argued to have a distinct biological function and not merely be a by-product, a collateral, of mitochondrial activity (**Figure 1**)[2-5]:

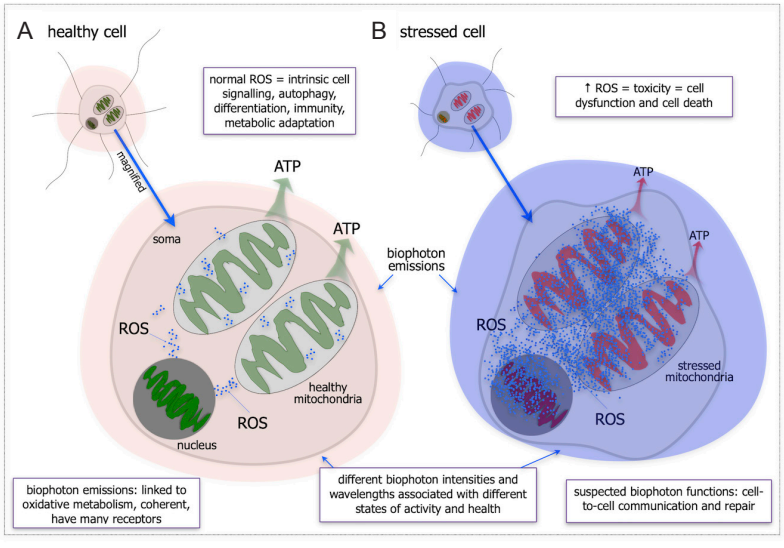

Figure 1: Patterns of biophoton emissions from cells.
Note: Biophoton activity has been linked to mitochondrial function, in particular oxidative metabolism (reactive oxygen species (ROS) production). When cells are functioning normally (A), adenosine triphosphate (ATP) energy production drives many cell functions and ROS participate in a range of important intercellular functions. When cells are stressed (B), ATP levels decrease and ROS levels increase, causing much cell damage. The biophoton activity changes also, seemingly mirroring the state of health of the cell. When cells become stressed, both the wavelengths (e.g. from red/infrared [A] to ultraviolet blue [B]) and intensity (i.e., increases, reflected by the darker shading of blue in B) of biophoton changes. For several reasons, including being linked tightly to oxidative metabolism, being coherent, and having many intrinsic receptors, biophoton emissions are thought to have a subserve a specific function, possibly in cell-to-cell communication and repair. This schematic was constructed using Apple Keynote programme.

(1) Of all the key metabolic reactions of the mitochondria, the ones involving ROS (oxidative metabolism) seem to be the main source of biophotons. Under normal circumstances, ROS have an important role in several cellular functions, including intrinsic cell signalling, autophagy, differentiation, immunity and metabolic adaptation; in essence, they maintain a critical balance of cell homeostasis. Under pathological conditions however, ROS levels are elevated and can become toxic, leading to cell dysfunction and subsequent death. Because the process of ROS generation is so precise, it has been suggested that the biophoton emissions serve as key indicators of oxidative metabolism.

(2) Biophoton emissions are considered to be highly structured (ie coherent), a feature that is generally viewed as a cooperation of many parts to subserve a particular function.

(3) The mitochondria - and various surrounding intrinsic cellular structures, such as ion channels - have distinct receptors that absorb light across a range of wavelengths (see below), including flavinic and pyridinic rings, lipids, aromatic amino acids, cytochrome c oxidase and interfacial water. These receptors, or chromophores, are present even among cells located very deep in the brain, regions where no external light can reach. Indeed, when external light, in the form of red and near infrared light, has been applied to cells deep in the brain there has been a distinct response, improving cell survival against neurodegenerative disease. Hence, one would think that these receptors are there in these organelles for a purpose, to use light to activate various intrinsic cellular mechanisms.

Taken all together, these reasons suggest strongly that there is a distinct biological significance for the biophotons.[2-5, 9-11]

Where do biophotons travel?

The biophotons appear to have two ways of travelling through the brain, over both long- and short-range distances. For long-range distances, biophotons seem to flow along the white matter pathways of the brain. These pathways often involve considerable distances, spanning between different lobes of the cerebral cortex and between the different centres of the brain, such as from the cortex to the brainstem and/or to the spinal cord. The amine pathways, including those using dopamine, serotonin or noradrenaline, seem to be most prevalent for biophoton emissions. For short-range distances, there appears to be some penetration of biophotons across the extracellular matrix. The distances involved for this flow are not clear, but given the weakness of the biophoton signal (see below), the distances are probably minimal, being in the micrometer range.[1]

The functions associated with biophotons

Although the precise function of biophotons is not entirely clear, there have been several speculations. First, that they form a means of cell-to-cell communication. Biophotons from one cell may inform other cells of their state of health or activity (**Figure 1**). They could influence functional activity, either exciting or inhibiting cells, either acting like a neurotransmitter directly or influencing the release of neurotransmitters at the synapse.[1-5, 12] Second, biophotons may also play a part in cell repair and regeneration. For instance, a stressed cell may release biophotons to repair itself or have biophotons from nearby healthy cells aide the repair process. The biophotons may help re-establish homeostasis and promote a resumption of normal cell function, as well as inducing cell growth and division.[4]

Biophotons may undertake both of these suspected roles by, for example, influencing many intrinsic cellular functions, including those associated with the mitochondria (i.e., ATP production and ROS levels) and/or ion channel activity.[1-5, 12]

Unfortunately, the evidence supporting both the communication and repair functions is weak, highlighting the real need for more research into this issue, particularly for neural cells. This will be explored further in a later section.

Biophotons and external light: is there a conflict of interest?

If biophotons do form a network of communication and repair between cells, it is worth considering how external light might influence this network.[4, 6, 13] Although most neural cells are not exposed directly to external light, residing in a cranial or vertebral cavity covered by bone and connective tissue, some neural cells, such as those in the retina and in the periphery innervating the skin, are indeed exposed directly to light. These retinal and peripheral sensory cells, unlike those encased in the darkness of bone and connective tissue, may have their biophoton network compromised. However, studies in the retina at least, have indicated that a biophoton network still operates with or without external light exposure.[13, 14]

Perhaps cells have developed a means of incorporating any external light exposure as part of their working biophoton system. Indeed, when exposed

to red to near infrared light, cells located deep in the brain – as indeed with those across the body – can generate a response (see above). It has been suggested that red and near infrared light, when applied to a living cell, improves cell function and survival, just as biophotons of similar wavelengths would do, albeit at much lower intensities, after being emitted from either the same or nearby cells.[4]

If we were to use an analogy, one could view external light exposure as the background noise that fills our environment and the biophoton network as the language communication between people. The different types of background noises that people may experience, whether they be loud, soft, pleasant (e.g., nice music) or not so pleasant (e.g., building construction), can certainly influence their behaviour and mood. More often than not however, regardless of the different types of background noise, people can still communicate with language, as well as adapt to the situation; for instance, if background noise levels are high, people can still communicate and may speak louder as compensation. Following this analogy, external light (e.g., red and near infrared) exposure can certainly influence cell function and survival (see above), and regardless of this exposure, cells may still communicate using biophotons and adapt to this situation. Cells may be able to distinguish external light and biophotons by using a range and/or combination of parameters, including wavelength, intensity and/or a currently unknown feature, just like people can distinguish between background noise and language. We have so much to discover about this cellular light system and we need the advanced technology to do so.

The Biophoton Technologies

Although first proposed about a century ago, progress into discovering more about the biophoton phenomenon – as with most areas of neuroscience research – has been limited by the technology available. The lack of effective technologies to reveal and define biophotons has no doubt contributed to a very sluggish development, together with a lack of widespread acceptance of the concept across the medical and scientific communities.

There appears to be two key elements underpinning this lack of technological progress in the field. First and foremost, the biophoton emission is extremely weak. It is not detectable with the naked eye nor with a fluorescence microscope. An ultra-sensitive detection system is required (see below). Biophoton emission intensities have been estimated to vary anywhere between 2–200 photons/s/cm^2 (**Figure 2A**). This emission appears to be in a rhythmic pulse-like pattern, not as a continuous wave (**Figure 2A**), and it can be increased or decreased (up to 100x) by an external stimulus for example, after electrical stimulation or the application of neurotransmitters, toxins or anaesthetics.[14-17] Second, setting up the optimum experimental conditions to detect the biophotons, given their extremely low intensity range, can be problematic. External light, whether from the room lighting source or from the detection/measuring device itself, can interfere with the biophoton readings. Photons from such external sources can linger – undetected by the naked eye - for a considerable period (i.e., hours), so there are clear issues in making sure the chamber or experimental room is pitch black, with no external photon contamination.[5]

In the section that follows, we will review some of the currently available technologies that determine two major aspects of the biophoton phenomenon, namely the patterns of intensity and the wavelengths. Following, we will outline some future prospects, addressing, what we consider, to be the key scientific and medical questions associated with biophotons.

Detecting and measuring patterns of biophoton intensity

To date, there are several ways of detecting and measuring the intensity of biophotons from living cells. These include photomultipliers, image detectors and with histological methods (**Table 1**).

Photomultipliers

Photomultiplier devices are by far the most common means of identifying and measuring biophoton activity. They detect the biophotons by, as their name implies, multiplying the signal from a given source (i.e., biophotons from living cells). Photomultipliers were developed from what was known a Geiger-Mueller tube, and operate in the following way (**Figure 2B**). Photons from a tissue sample are acquired through a glass window that covers a photocathode (i.e., photosensitive surface) and they enter a vacuum tube. Along the course of the tube, there are curved electrodes that are held at increasingly higher voltages. As the photons enter the tube, there is a release of electrons, that are then multiplied, through the kinetic impact, onto the next electrode along the tube. At the end of the electrode chain there is an anode or collection electrode. The current flowing from the anode to ground is directly

proportional to the photon-electron flux generated by the photocathode. The resultant millions of electrons at the end of the process are read out as a current. In this way, photons are detected and any changes in their intensity under different conditions (e.g., normal or stressed) can be recorded.[5, 18, 19]

Table 1: Outline of the advantages and disadvantages of each technology associated with biophoton detection

Technology	Method of detection	Advantages	Disadvantages	References
Photomultipliers	● Multiplying signal from a given source (i.e., biophotons from living cells) ● As photons enter device, there is release of electrons, that are then multiplied ● The resultant millions of electrons at end of process are read out as a current	● Real-time outputs ● Covers a relatively large detection area ● Has a low dark-noise per unit detection ability (signal-to-noise ratio of 40–100 photon/s detection rate)	● Quantum efficiency is not great (1%–40%) ● Cannot capture images	Mould et al.[5]; Ma et al.[18]; Pelletier and Pelletier[19]
Image detectors	● Ultra-sensitive camera with an added special electron multiplication output register (latter similar to photomulitplier) ● Has a silicon sensor chip that maximizes number of electrons generated from a light source. The chip has pixels that are charge points after light exposure, charges in the pixels are transferred to a storage region where the image is read. ● Each pixel is transferred to the multiplication register, that amplifies each pixel several thousand times	● Can capture images ● Limits detrimental readout noise that is intrinsic to all imaging devices, making them more sensitive and more suitable for biophotons.	● Process of acquiring an image can take a long time, sometimes hours; any movement of tissue hampers image quality. ● Photon counts are less accurate than photomultipliers ● Some concerns regarding the multiplication method	Mould et al.[5]; Wang et al.[13]; Sun et al.[20]; Zapata et al.[21, 25]
Histology	● Using *in situ* biophoton autography ● Relies on the reduction of Ag^+ to Ag after light exposure (i.e., biophotons) ● Presence of Ag is considered to mark sites of photon activation in tissue	● Can be identified with a standard light microscope ● Cost effective and readily available	● Accuracy of method needs further exploration ● Some issues on how reduction process of Ag^+ to Ag affects the tissue and whether it can influence biophoton count	Salari et al.[15]; Zangari et al.[16]; Sun et al.[20]

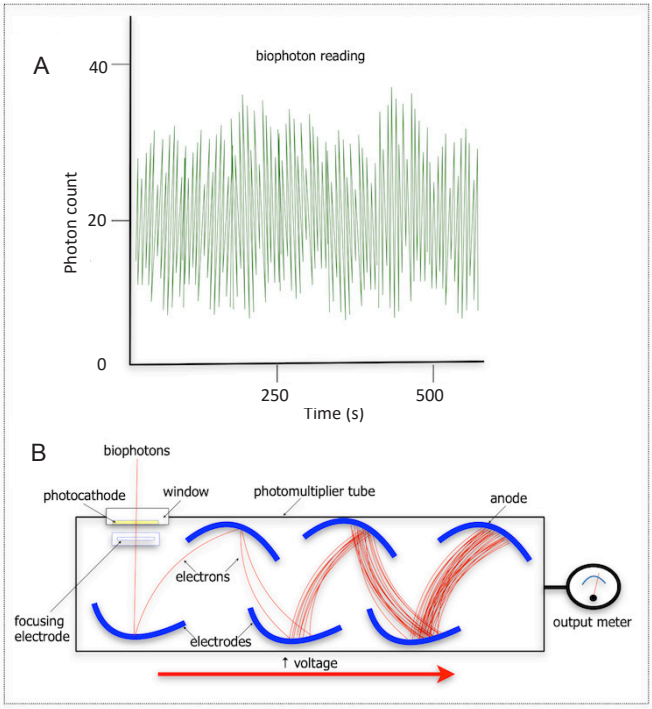

Figure 2: Schematics of (A) a typical biophoton intensity reading (at rest) from cultures of living cells using a photomultiplier and (B) the basic mechanism of a photomultiplier (the most common device used to detect biophotons). Note: Photomultipliers, as their name implies multiply the signal, converting photons to elections and amplifying the signal (A). This is particularly useful for biophotons where the signal is so weak, often averaging ~20 photons/s at rest (B). The biophoton signal is typically rhythmic and pulse-like, not as a continuous wave of light, and it can increase or decrease considerably after external stimulation. This schematic was constructed using Apple Keynote programme.

Photomultipliers have advantages of giving real-time outputs, cover a relatively large detection area and have a low dark-noise per unit detection ability; they have a signal to noise ratio at the 40–100 photon/sec detection rate, well within the biophoton range. Their quantum efficiency is not great however, being in the range of 1–40% (most efficient for visible light and weakest for infrared). Further, they cannot capture images. To sum up, notwithstanding some limitations, the photomultipliers are the go-to device for biophoton detection.[5, 18, 19]

Image detectors

Although photomultipliers remain, at present, the best way to count photons from living cells, they cannot capture images. In recent times there has been some progress however, with the development of sensitive image detection systems linked to electron-multiplying technology; these in general, can not only count photons, although not as effectively as photomultipliers, but generate images as well.[5, 11, 20, 21]

Perhaps the best known of this type of technology has been called an electron multiplying charge coupled device (EMCCD; **Figure 3**). This is essentially an ultra-sensitive camera with an added special electron multiplication output register. This device limits the detrimental readout noise that is intrinsic to all imaging devices, making them more sensitive and more suitable for biophoton research. The readout noise is a problem because it is similar to the signal of a few photons, mimicking the presence of biophotons. By amplifying the signal, using the electron multiplying technology (similar to photomultipliers), the EMCCD render the readout noise negligible. The EMCCD has a silicon sensor chip that aims to maximise the number of electrons generated from a light source. The photons are converted in, what has been called, the imaging region of the chip. The chip is organised into pixels that are seen as charge collection points generated by the photoelectric effect. After the light exposure, the charges in the pixels are transferred across the sensor from the imaging region to the storage region. This storage region is where the image is read. Here, each pixel is transferred into the multiplication register, that amplifies each pixel several thousand times. Finally, photoelectrons reach the output amplifier where they are converted to a voltage and digitised to form an image.[5, 11, 20, 21]

Hence, by nearly all accounts, this EMCCD system seems the ideal technology and, thus far, has generated the most detailed images of biophotons. As with most technology, there are some problems and these centre principally on the main issue associated with biophoton research, the low photon count (NB: this will be a recurring theme). First, the process of acquiring an image can take a long time, sometimes hours, and hence any movement of the tissue generates issues of image quality. Second, the photon counts with EMCCD are considered less accurate than those obtained with photomultipliers and there are some concerns regarding the multiplication method used by EMCCD. Notwithstanding these issues, this technology holds much promise and there is scope for improvement and opportunities for further development.[5]

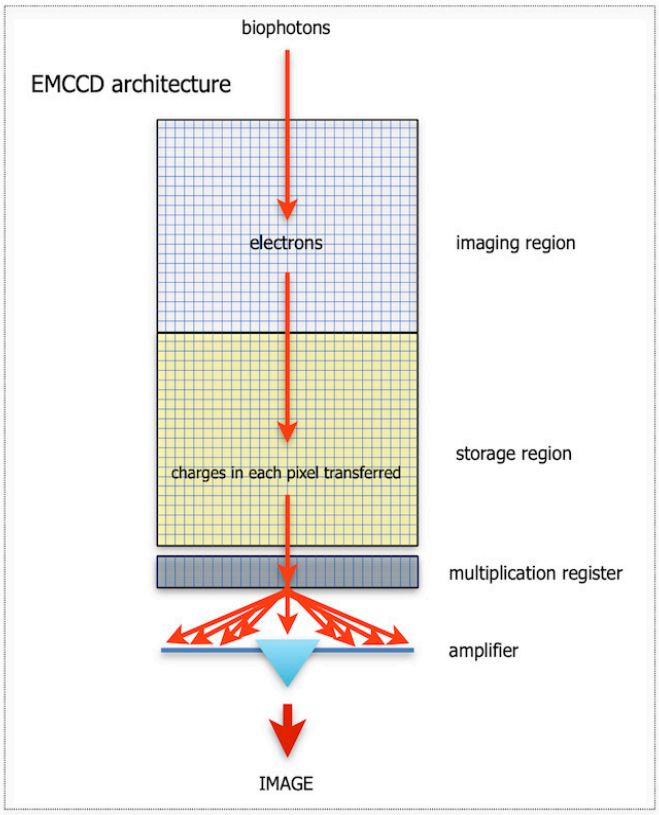

Figure 3: Schematic diagram of the basic mechanism of an EMCCD. Note: Photons are converted into electrons across the imaging region. This region is organised into pixels, that are seen as charge collection points. After light exposure, the charges in the pixels are transferred to the storage region where the image is read. Each pixel is then sent into the multiplication register, that amplifies each pixel several thousand times. Next, photoelectrons reach the output amplifier where they are converted to an image. This schematic was constructed using Apple Keynote programme. EMCCD: Electron multiplying charge coupled device.

Histology

A recent, rather fascinating, approach for the detection of biophotons is with the use of histology, in particular using the method of *in situ* biophoton

autography.[15, 16, 20] Similar to developing images in photography, this method relies on the reduction of Ag^+ to Ag after light exposure (ie biophotons). The presence of Ag is considered to mark sites of photon activation in the tissue and can be identified with a standard light microscope.

In this experimental set-up, the living tissue is placed in a dark room/chamber and processed for both biophoton activity using EMCCD and then for *in situ* biophoton autography; in this way, the Ag deposits can be quantified and correlated with the analysis generated by EMCCD. In general, there seems to be a good correlation between the two methods. Indeed, it has been argued that the histological method may be more sensitive.[15, 16, 20]

This methodology is potentially very exciting in that here we have an accessible and relatively inexpensive technique available for the detection of biophoton activity. However, the accuracy of the method needs further exploration and there are some issues on how the reduction process of Ag^+ to Ag affects the living tissue and whether it can influence the biophoton count.

Defining biophoton wavelengths

A major challenge in trying to decipher the significance of the biophoton emissions is the determination of the wavelengths involved. To this end, previous studies have reported that the wavelength spectrum associated with biophotons is rather broad, encompassing the ultraviolet to red and near infrared range (i.e., ~200–950 nm).[4, 5]

As with the intensity of biophotons (see above), the associated biophoton wavelengths can change depending on the state of activity and health of the cell (**Figure 1**). For example, ultraviolet and visible light (eg blue, green and red) have been linked with stages of cell growth. Further, with increasing time periods, cells in culture show an initial stage of infrared biophoton emission (possibly linked with cell repair and survival?), followed by a later stage of ultraviolet emission (possibly linked with the process of cell death?) (**Figure 1**).[22, 23] In addition, there are distinct differences in both the numbers and wavelengths of biophotons evident between cancerous and non-cancerous cells; cancerous cells tend to emit ultraviolet light while non-cancerous cells emit infrared.[24] These early findings, indicating a broad range of wavelengths reflective of cell homeostasis and type, open many potential diagnostic and therapeutic avenues of exploration (see below).[4, 5, 14]

The main way in which previous studies have defined the biophoton wavelengths has been using band-pass filters on a photomultiplier. Most photomultipliers have a wavelength sensitivity range from 250 to 1000 nm. Depending on the wavelength to be measured, the appropriate band-pass filter can be placed on top of the aperture before exposure. The band-pass filters that have often been used are between 350 to 950 nm, wavelengths that extend across the ultraviolet to red and infrared range.[14, 22-24]

Although the additions of these band-filters provide invaluable information regarding wavelength, there are some sacrifices. In particular, because of the low counts of photons involved (ie the recurring problem!), each additional optic used in the experimental set-up causes further loss of sensitivity and a diminished signal.[5]

What does the future hold? Exploring the biophoton technologies that can be developed

As we see it, there are three main avenues for further research and development for the biophoton phenomenon. First, to define conclusively the function of biophotons (if any), that they are involved in cell-to-cell communication and repair, particularly for neural cells; second, to better define the *in vivo* biophoton output in the whole organism, particularly humans; and finally, to develop a device for clinical use, and the living brain, to detect and treat neurological ailments. These will be considered, in turn, below.

Biophoton function

Although there is much circumstantial evidence, as it stands, there is nothing conclusive showing that the biophoton emissions are indeed used for communication and/or repair in living cells, particularly neuronal cells. For communication, the best evidence available is from various experimental findings showing diminished patterns of growth and stress response when two groups of cells, either plant or bacterial, are separated by a barrier (eg thick glass); the rest of the evidence is rather indirect and circumstantial.[1-5] For repair, the evidence is even weaker, relying on the premise that externally-applied red or near infrared light – same wavelengths used by biophotons – can improve cell survival against ageing or after stroke, traumatic brain injury and/or neurodegenerative disease.[4, 11]

The main reason why stronger evidence for a communication or repair role for biophotons has been not so forthcoming over the past few years is because

it is technically challenging. It is a challenge in itself to just detect the biophotons from living tissue, so to combine another method to the set-up presents even further complications. This is particularly the case if there is an addition of a functional method, for example electrophysiology, because such methods present a series of technical challenges in themselves. Nevertheless, an experimental paradigm could be developed to include cell cultures, set-up side by side, one measuring biophotons and the other recording functional and/or mitochondrial activity; cellular stresses (e.g., toxins) could be applied to the biophoton cell culture and recordings/measurements, with or without and an intervening glass barrier, could be made in the other cell culture.

Such endeavours, combining biophoton and other functional technologies, would go a long way in establishing biophotons as a key component to understanding overall brain function and intercommunication. That together with chemicals, electricity and gases, light could be considered a major form of communication between neural cells and that these cells can use light to repair themselves and others nearby.

Biophotons in vivo; the whole organism

Most of the previous investigations on biophotons have been either in cell culture (e.g., bacteria, fungi or neural cells) or in plants. There are some studies however, that have explored the pattern of biophoton emissions in the whole organism, humans in particular.[21, 25] These studies have examined the biophoton output in individuals with different ailments or conditions – for example mood states, hemiparesis and diabetes – and compared their readings to controls. In each case, differences were noted in the biophoton emissions between the experimental and control groups. For example, in hemiparesis patients, weaker biophoton emissions have been detected on the side of the paresis, compared to the "normal" side. The technology used was a spectrograph connected to a dark-noise astronomy high-sensitivity charge coupled device camera. These early results are very encouraging and pave the way for further exploration and development. A way forward would be to examine the wavelengths involved in the different conditions and ailments compared to controls.

Biophotons in the clinic: therapeutic implications

Although much remains unknown regarding the precise significance of the biophoton emissions, the potential therapeutic implications are considerable.

One can envisage a non-invasive transcranial device being able to read biophoton signals from the underlying brain tissue **(Figure 4A and B)**. Such a device could be developed to decipher and screen the different layers, that is hair, bone and connective tissue, and focus on brain tissue. The device could incorporate a depth range so as to screen, not only superficial regions of the brain such as the cerebral cortex, but also deeper regions, such as the thalamus and brainstem. The device would essentially be reading the wavelengths and intensities of biophoton emissions – in a similar way to a photomultiplier **(Figure 4A and B)** – that reflect the cellular patterns of oxidative metabolism and overall mitochondrial health. Such a device could be similar to the recently developed, so-called dodecanogram, that detects ultra-low-power electromagnetic radiation from different locations on the surface of the brain.[26, 27]

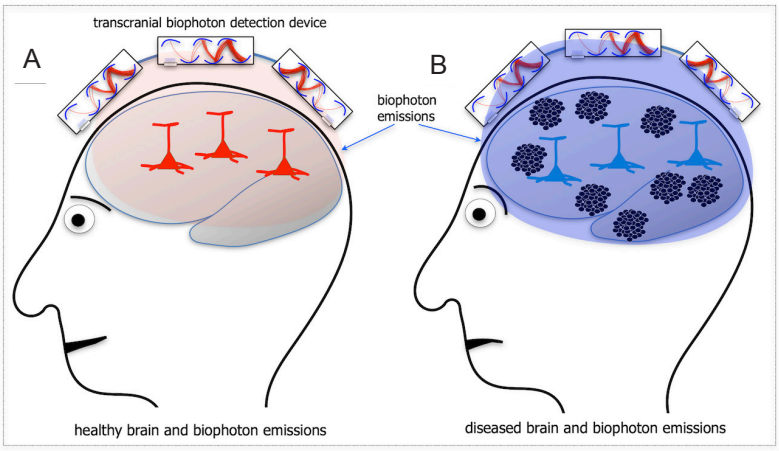

Figure 4: Schematic diagrams of a potential transcranial biophoton detection device of the future in (A) a normal healthy brain and (B) a diseased brain (e.g., Alzheimer's disease; the collections of black small circles represent amyloid deposits).
Note: These different conditions could be associated with biophotons of different wavelengths and intensities (represented by different colours and levels of darkness of the biophoton emissions in A and B). This device could be developed to decipher the different layers through the cranium and focus on brain tissue. It would screen – through the biophoton emissions, similar to how a photomultiplier works – the cellular patterns of oxidative metabolism, reflective of mitochondrial health. The development of such an ultra-sensitive biophoton detection device could then guide therapeutic intervention. This schematic was constructed using Apple Keynote programme.

The development of an ultra-sensitive biophoton detection device could then guide therapeutic intervention (eg drug therapy, targeted red and infrared light treatment or neurosurgery) depending on the neurological condition, whether it be stroke, traumatic brain injury, mental illness or neurodegenerative disease **(Figure 4A and B).**[4, 11] In this context, a rather novel approach has been suggested recently, using a brain computer interface photonic chip.[28] Such a chip, that would be minimal invasive, would be able to screen biophoton emissions and guide therapy in much the same way as described above.

Limitations

Our work has some limitations. First, being a narrative review, we have presented a more subjective analysis of the technologies available to detect biophotons, together with the biophoton phenomenon itself. It is by no means an exhaustive, in-depth venture, but rather, a general exploration into the main technological issues associated with the field. We felt that a narrative review would be more appropriate at this time, given that there is so little concrete evidence of the significance of biophotons. Second, a considerable part of the review is speculative. For instance, we consider the future development of devices that can detect biophoton emissions for clinical use in the brain of living humans. Overall, we are hopeful that our review can inspire and generate future research into this area and the development of novel devices associated with the detection of biophotons.

Conclusions

In summary, as with many areas of neuroscience, progression in the research field of biophotons has been plagued by the limitations of available technology. The devices to reveal biophoton emissions - although much improved in recent times - have struggled, and are still struggling, to deal with their biggest problem; a very weak signal, made up by only a handful of photons, from cells. However, the technology is ever developing and it is hoped that in the foreseeable future, the mystery of the precise significance (if any) of the biophoton emissions is unravelled. In particular, evidence to support the concept that biophotons – across a range of wavelengths, from ultraviolet to infrared – serve as; first, a means of cell-to-cell communication, informing on different states of activity or health, and; second, a way in which cells may repair themselves or others nearby if they are in distress. These endeavours can pave the way for clinical application, where ultra-sensitive biophoton detecting devices can be developed to screen mitochondrial health in stressed cells in humans. Such devices would aide in the detection and subsequent treatment of a range of neurological conditions, from stroke to traumatic brain injury and from mental illness to neurodegenerative disease.

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Author contributions

JM drafted the article. JM and JHK performed the literature search. All authors contributed to the writing and critical revision of the manuscript, and approved the final manuscript.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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Data availability statement

Not applicable.

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