

Introduction: Bridging Physics and Dermatology As a clinician working in the field of dermatology, my work takes place at the boundary between a person and their environment, the skin. I observe its constant interaction conversation with the environment, its resilience, fragility, and capacity to heal. The most powerful participant in that interaction is light. A single day at the beach can transform the skin, for better or worse, through a process explained through the language of biology and chemistry being ultraviolet (UV) energy, oxidative stress, and DNA damage. Yet, as physicist Alex Comfort wrote in his 1984 essay “Quantum Physics and the Philosophy of Medicine,” the intellectual framework of medicine often lags behind the frontiers of science.¹ He commented that much of medicine remains grounded in frameworks from the previous century, rooted in classical biology and reductionist models of disease, despite the rapid evolution of modern science.¹

This observation remains profoundly true today. While the integration of quantum technologies into health-care is emerging as a transformative force, a deep divide still separates fundamental physics from clinical practice. Our clinical models are built on classical foundations. Yet the very processes we seek to understand being the interaction of a photon with a molecule, the transfer of an electron, and the genesis of a mutation, are governed by the counterintuitive principles of quantum mechanics.

The foundation of chemistry rests on quantum physics. The stability of the molecules we prescribe and the bonds we study are direct consequences of quantum laws. The central question driving the emerging field of quantum biology remains. Does quantum physics influence life beyond this foundational level, shaping the very phenomena that defines living systems? Is life merely constructed upon a quantum stage, or is it itself an active and sophisticated quantum player?

To truly understand the skin, we must adopt the latter view. The principles of quantum mechanics are not merely relevant but essential to explaining the skin’s fundamental processes of photoprotection, photodamage, and phototherapy. Within the practical and clinical context of dermatology, I will explore two key questions. Do skin cells harness quantum phenomena to withstand their relentless exposure to light? And can the field of dermatology ever be complete without a quantum mechanical framework?

I contend that meaningful progress in understanding the role of quantum physics in biology will require the creation of new tools, methodologies, and conceptual frameworks at the intersection of physics, chemistry, and biology. The skin’s continual renewal and responsiveness to environmental stimuli depend on finely tuned patterns of gene expression, largely regulated by epigenetic mechanisms.² It is at this molecular scale that quantum effects may exert a decisive influence. From a clinical standpoint, I will also propose experimental approaches to explore these ideas in an attempt toward a future in which medicine can begin to diagnose and treat at the quantum level.

Quantum Photobiology and its Relevance to Dermatology To ask whether biology employs quantum advantages is to ask whether evolution has learned to harness phenomena such as superposition or ultrafast energy transfer, processes that have no classical equivalent. If quantum physics plays a role in biology, in which systems do this occur, and at what level? In dermatology, we need look no further than the molecule at the core of photoprotection, melanin.

The skin interacts consistently with light, making photobiology being the study of these interactions central to dermatology. When these interactions are viewed through the lens of quantum mechanics, a deeper and more fundamental understanding emerges, illuminating processes from sun protection and DNA damage to the principles underlying light and energy-based therapies. This perspective reflects a growing movement to integrate quantum mechanics into medicine, acknowledging that the biological changes underlying disease ultimately arise from quantum events at the nanoscale.³

Melanin: A Quantum Sunscreen Classically, melanin is described as a cellular pigment that absorbs and scatters UV light. As the principal natural defence against UV radiation, its role is often described in classical terms. However, this description is incomplete. The utility of melanin lies in how it manages the energy of absorbed UV being quantum mechanical in nature.⁴ When a photon strikes a melanin molecule, it excites an electron to a higher energy state. If this energy persisted, it could trigger harmful chemical reactions such as the generation of reactive oxygen species (ROS) that damage the cell.⁵

However, melanin possesses additional properties. Through a quantum process known as ultrafast internal

conversion, the molecule funnels this excitational state into vibrational energy on a timescale of femtoseconds to picoseconds.⁵ This quantum advantage enables an extraordinarily rapid and efficient energy decay, ensuring that nearly all absorbed photons are neutralised before they can cause damage. It is arguably the most perfect natural sunscreen, and its effectiveness stems directly from its quantum mechanical properties.

Yet, this quantum story has a darker side with direct clinical consequences. Two main types of melanin exist in the skin, brown-black eumelanin and red-yellow pheomelanin. Individuals with fair skin and red hair, being those who predominantly produce pheomelanin, face a markedly higher risk of melanoma.⁶ The reason is quantum. While pheomelanin still absorbs UV light, it is far less efficient at ultrafast heat dissipation. A significant fraction of its excited states decay through pathways that generate ROS, resulting in cellular damage. These quantum-level differences in excited-state dynamics can be probed using electron paramagnetic resonance (EPR), which detects the unpaired electrons responsible for melanin's paramagnetic properties.^{4,5} EPR spectra distinguish between the semiquinone radicals of eumelanin and the semiquinonimine-type radicals of pheomelanin, providing a mechanistic explanation for a clinical observation that classical biology can describe but not fully explain.⁴

When Quantum Events Harm DNA The quantum narrative extends to our genetic code. The primary driver of skin cancer is UV-induced DNA damage, most commonly the formation of cyclobutane pyrimidine dimers in which adjacent DNA bases become improperly fused and disrupt normal DNA replication. This process begins with a single quantum event being the absorption of a UV photon by a DNA base, which excites an electron to a higher energy state. It has been suggested that this energy can become delocalised across several adjacent bases as a quantum superposition, or "exciton." The site where this quantum state ultimately collapses determines the location of the chemical lesion. The epigenetic consequences of such UV damage, including changes in DNA methylation patterns are well documented, contributing to disruptions in skin homeostasis, premature aging, and carcinogenesis.²

Here, the quantum nature of this process represents a vulnerability. Understanding the dynamics of DNA excitonic states, how they propagate and where they are likely to localise, may explain why certain DNA sequences become mutational hotspots following UV exposure. Classical physics can describe the resulting kinked DNA strand, but only quantum mechanics can reveal how and why that kink forms in the first place.

Beyond Classical Models: The Necessity of a Quantum Framework

Consider the challenge of decoherence. A common objection to quantum biology is that the noisy cellular environment should rapidly destroy delicate quantum coherence, rendering it irrelevant. However, how might decoherence be delayed within the cell? We can look to the skin to provide a potential answer. In keratinocytes, melanin is not free-floating but packaged into highly organised organelles called melanosomes, while nuclear DNA is tightly packed into chromatin. It is plausible that such intricate structures evolved, at least in part, to protect functional quantum processes from environmental decoherence. From this perspective, the cellular environment is not merely noise but is instead a structured and integral component of the quantum system.

The reach of quantum biology in dermatology extends beyond photoprotection and DNA damage to cellular sensing and therapeutic intervention. Low-Level Laser Therapy (LLLT), also known as photobiomodulation, is a type of treatment that employs red or near-infrared light to accelerate wound healing and reduce inflammation.⁷ While the precise mechanism remains debated, a compelling quantum biological model suggests that photons from LLLT are absorbed by cytochrome c oxidase in the mitochondrial electron transport chain.⁷ This interaction may facilitate quantum tunneling of electrons, enhancing mitochondrial function and boosting ATP production. If correct, this quantum perspective could transform light-based therapies, shifting from trial-and-error approaches to strategies grounded in precise quantum control of cellular processes.

Cutaneous photoreceptors provide a striking example of quantum biology at work. Cryptochrome proteins, well known for their role in avian magnetoreception, are also present in human skin cells where they contribute to the peripheral circadian clock.⁸ It is plausible that these skin cryptochromes operate via the same light-induced radical pair mechanism, meaning our skin might detect light through a quantum process, influencing local metabolism and gene expression. This raises the intriguing possibility that the skin could also be modulated by factors affecting quantum spin dynamics, such as weak magnetic fields.

A complete description of biological function must also account for complexity and information. How can we define the complexity of a skin cell? How can correlations between quantum features, cellular complexity and entropy be measured? It is possible that cellular homeostasis depends on the ability to maintain low entropy and high efficiency by leveraging quantum pathways? In this context, UV-induced DNA damage is not merely chemical but also thermodynamic by introducing entropy that disrupts the cell’s quantum machinery. Emerging work in quantum thermodynamics may provide the conceptual framework needed to link the quantum states of a cell’s molecules to overall cellular health and complexity.⁹ Some theories even propose that DNA itself functions as a highly efficient quantum computer, using oscillatory resonant states and Josephson junctions between base pairs to process information, suggesting a level of biological computation far beyond classical understanding.⁹

Translating Quantum Insights into Clinical Practice Decisive advancements in this field necessitate the development of innovative tools and methodologies at the intersection of physics, chemistry and biology. Moving from theory to practice requires experiments that can probe quantum phenomena within the complex environment of a human cell. Here, I propose three novel experimental directions that could advance our understanding of quantum processes in dermatology.

1. Mapping a quantum signature of melanoma risk The protective advantage of eumelanin over pheomelanin arises from their distinct quantum properties which may be directly measured. Using two-dimensional electronic spectroscopy (2DES), a technique employing ultrafast femtosecond laser pulses to map energy flow within molecules,¹⁰ melanosomes extracted from skin of varying tones could be analysed to visualise differences in energy dissipation. Comparison of these 2DES maps would reveal the quantum pathways that safely dissipate energy in eumelanin versus those that generate ROS in pheomelanin. Clinically, this approach could enable a personalised quantum melanoma risk score that reflects an individual’s melanin signature. It could also guide the development of tailored sunscreens designed to replicate eumelanin’s ultrafast harmless energy dissipation, leveraging principles of quantum mechanical drug design.

2. Designing a quantum quencher for DNA protection If we can observe the initial quantum state of DNA following UV absorption, it may be possible to design molecules that intercept this energy before damage occurs. The formation of a DNA lesion occurs on a picosecond timescale, but the preceding electronic dynamics are even faster. Using attosecond spectroscopy, which can track electron movement on its natural 10^{-18} -second timescale,¹¹ we could study DNA oligonucleotides in real time to observe how the electron cloud reconfigures after UV exposure and how energy localises to form a lesion. Insights from this experiment could enable the design of quantum quencher molecules for use in sunscreens. These molecules would not only absorb UV light but also be tuned to the specific energy of the DNA excited state, effectively diverting energy away from DNA and dissipating it safely. This approach would represent a paradigm shift from passive photoprotection to active quantum-level intervention.

3. Developing a quantum biomarker for skin aging Photoaging reflects the long-term consequences of oxidative stress, a phenomenon governed by quantum mechanics. To measure the quantum byproducts of this stress in living tissue, quantum sensors such as nitrogen-vacancy centers in diamond¹² can be used to map local magnetic fields generated by ROS in real time. These sensors are incredibly sensitive and, when placed in contact with ex vivo skin cultures, could measure ROS production under UV stress with subcellular resolution. This builds on studies using quantum dots to track ROS generation in skin cells, which have demonstrated the feasibility of nanoparticle penetration into intact epidermal and dermal tissue.¹³ Clinically, this approach could provide a quantum biomarker for cumulative photodamage and overall skin health. It would allow early quantification of photoaging and real-time assessment of antioxidant therapies by linking quantum features, such as spin dynamics, to biological measures of cellular complexity and entropy.

Conclusion “How quantum is life?” is no longer merely a philosophical question as it has practical and profound implications for medicine. Through the lens of dermatology, we see that life is indeed a quantum player. The skin is a dynamic quantum system. Melanin confers protection through ultrafast energy dissipation, while DNA reveals vulnerabilities in its quantum response to light. A complete picture of skin biology and dermatology must therefore be quantum-informed. As Alex Comfort noted in his 1984 paper,¹ when biology and medicine lost contact with physics, understanding stalled. It is time to re-establish that connection.

Evidence suggests that biological systems exploit quantum rules to their advantage, from energy transfer in melanin to potential quantum compasses in cryptochromes and mitochondria. Translating these principles into clinical practice requires bridging the physicist's lab and the clinician's office. The experimental approaches proposed here, including mapping the quantum dynamics of melanin, visualising DNA lesions in real time, and developing quantum sensors for oxidative stress, illustrate how this translation might occur. By incorporating quantum insights, these studies may open the door to a new era of precision medicine, such as sunscreens that quench damaging excitational DNA states, therapies that exploit cellular quantum dynamics, and diagnostics capable of sensing subtle quantum signals in disease.

Quantum biology is poised to reshape our understanding of life and medicine. By probing the quantum nature of biological processes, we can not only solve enduring mysteries but also open a new era of personalised and mechanistically-driven dermatological care. The answers to life's deepest quantum puzzles may lie in our own skin, and in solving them, we will not only advance science but also importantly improve the care we provide to our patients.