



SEAMLESS CHEMO-ELECTRICAL AND RADIATIVE INTERFACING OF 'LIVING ORGANIC SYSTEMS' WITH 'MAN-MADE ELECTRO-MECHANICAL COMPONENTS' VIA MURBURN CONCEPT

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*Life-sustaining mechanisms were primarily understood within the purview of: (i) intelligent cellular/organellar membranes guarding/maintaining their internal milieu deterministically, and (ii) the cellular activities being governed by directional information-flow via the central dogma. In this schema, cellular coherence (inter-molecular networking to achieve functional unitization) and homeostasis/electrophysiology were explained by the concentration-dependent interaction unidirectional positively correlated dynamics of catalytic enzymes-substrates, electron donors-acceptors, signalling receptors-ligands, channels-ions, antibodies-antigens, etc. Such treatments entailed selective/specific and topology-based (affinity-driven) stoichiometric interactions. Also, only the impact of external radiations (like X-rays, UV-Vis-IR light, micro/radio waves, etc.) on living systems have found prominence in biomedical literature, with lesser information on internally generated or readdressed low/high-frequency radiations. The above long-standing paradigm has witnessed a major upheaval in the last decade with the unravelling of murburn concept, which postulates that diffusible reactive species (DRS) and murzymes (proteins that recruit DRS in routine functions) are a fundamental pivot of life that aid catalytic moiety-/electron-transfers, phase-changes, post-translational modifications, etc. within the cells, thereby serving diverse agenda of its function. The murburn theorization solicits cellular "Chemico-Electromagnetic Matrix (CEM) with "molecule-unbound ion-radical/radiation interactions", which provides powering and coherence for living systems, and explains why oxygen became the elixir of life. Herein, we project tangible framework/examples of how murburn concept could afford a seamless interlacing of man-made synthetic components with biological systems, particularly within the contexts of intelligence/controls, bioenergetics, metabolic and sensing-response agenda. We also discuss mandates wherein analog-digital conversions could be achieved, and project the scope and limitations of murburn-based approach in futuristic bionic-cyborg technology. **Biomed Rev 2025; 36: 31-43***

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I. INTRODUCTION

Norbert Wiener's (1948) work launched the field of cybernetics, focusing on how systems—both biological and artificial—use feedback to regulate themselves. His theories laid the groundwork for robotics, AI (artificial intelligence), and modern brain-machine interface technologies. Kevin Kelly (1995) prophetically wrote- "*We are creating machines that resemble living systems, and we must embrace this evolution. Biological principles—self-organization, cooperation, and adaptability—are the future of man-made systems.*" Kelly compared biological ecosystems to machines, demonstrating how lessons from nature (like ant colonies or immune systems) can inspire innovations in AI, robotics, and hybrid systems. He also foreshadowed developments in swarm robotics and distributed intelligence. In 1998, Kevin Warwick became the first human to connect his nervous system directly to a computer network. The experiment allowed him to control devices and experience sensations remotely, paving the way for bionic integration. Warwick's (2002) groundbreaking experiments in neural implants and brain-computer interfaces brought the idea of cyborgs from theory to reality. His work emphasized the feasibility of merging biological and artificial systems for medical, military, and societal applications. In his book, Andrew Clark (2003) argued that humans have always been "cyborgs" due to our propensity to integrate tools and technologies into our cognitive processes. He discusses the transformative potential of this integration and its implications for the future of human intelligence. It is a cornerstone of philosophical and cognitive science, and lays the groundwork for understanding the seamless blending of biological and artificial systems by framing the mind as inherently adaptive and extendable. He introduced the "Extended Mind Hypothesis", arguing that the boundary of the mind is fluid and includes external tools (how technologies like writing, calculators, and now neural implants are extensions of human thought). It shifted perspectives in neuroscience, cognitive science, and bioengineering, encouraging research into how biological and artificial systems can be symbiotic rather than competitive. Wu et al. (2013) discussed the merging of AI and biological intelligence (BI), highlighting the challenges and opportunities in creating systems that seamlessly integrate biological fundamentals into machine operations. Further, in their paper focusing the introduction of cyborg intelligence, they proposed a hierarchical framework based on the interaction between biological cognitive units and computational intelligent units, offering insights into the theoretical underpinnings of such

integrations (Wu et al., 2016). Exploring the fusion of AI with BI through brain-machine interfaces (BMIs), Shi et al. (2016) discussed the implementation of systems where biological entities and machines collaborate, providing a foundation for integrating biological principles into machine logic. A recent preprint by Talanov et al (2022) reviews the advancements in neuromorphic technologies and brain-computer interfaces, proposing a "Neuropunk revolution" that envisions a new generation of approaches to integrate cybernetic objects with biological tissues. It provides a perspective on the future of human-machine integration.

Over the past several years, our group has advocated that effective charge separation (ECS) forms the most fundamental thermodynamic drive of life forms, leading to the obligatory production and involvement of diffusible reactive species (DRS, some of which are also called reactive oxygen species or ROS, in aerobic systems) in physiology. This broad view of looking at cellular life process was called murburn concept. We theorized that the holistic integration of cellular powering, coherence, homeostasis, electro-mechanical and sensing-response (PCHEMS) activities proceeded obligatorily via DRS, enabling the cells to function with a "Chemico-Electromagnetic Matrix (CEM), and serve as simple chemical engines (SCE), without "overt deterministic intelligence" governing functionalisms at the acute timescales [Manoj & Jaeken, 2023; Manoj et al., 2023a,b; Jaeken & Manoj, 2025]. In recent literature, it has also been proposed that there could exist "digital-type biological circuitry" in cellular systems [Penketh, 2022, 2023]. These two nascent and fundamentally radical ideas provide a new window of opportunity in bionics-cyborg research, and the potential fusion of these emerging ideas is the focus of the current futuristic projection write-up. We believe that this article could form a monumental step towards the material realization of Kelly's (1995) "*The line between the born and the made is disappearing*", Clark's (2003) "*There is no sharp divide between BI and external devices; instead, we achieve a kind of biological-machine co-evolution.*" and Warwick's (2003) "*Cyborgs aren't just science fiction. They're here, and they represent the future of human evolution.*" statements.

II. THE CLASSICAL VIEW OF LIFE-SUSTAINING MECHANISMS AND BI

Arguably, the most pivotal aspect of a living cell's functioning is "powering", which is the modality used by the organism for availing resources from the environment to perpetually

execute its “will”, apparently exerting against the forces of equilibrium that constantly work to undo cellular organization and function. The highly acclaimed classical explanations for cellular powering (whether by photosynthesis in thylakoidal membranes OR respiration in mitochondrial membranes) rests on: (i) electron transport chains (ETC, a deterministic electronic relay circuitry of immobile/mobile protein/biomolecular agents embedded in or distributed around phospholipid membranes), (ii) directional proton(ion)-pumping/channelling to generate electro-chemical gradients, and (iii) harnessing of such an ionic gradient thereafter by proton(ion)-translocating rotary machineries that perform chemical (synthesis of ATP) or mechanical (bacterial flagella-assisted motility) work, and/or generate thermal energy (by uncoupling proteins or thermogenins) [Alberts et al., 2008; Berg et al., 2002; Nelson & Cox, 2004; Voet & Voet, 2011]. Since 2017, we systematically pointed out the infeasibility of such mirage-like proposals, pointing out that they lack foundations in reality and are based on misinterpreted observations. We specifically highlighted multitudes of untenable aspects of the “ETC-CRAS (chemiosmotic rotary ATP synthesis)” bioenergetics proposal [Manoj group’s publications from 2017 to 2024]. Specifically, the features- (i) violating fundamental principles of thermodynamics, (ii) lacking spatio-temporal (kinetic) viability, (iii) demonstrating the mechanistic incompatibility of structure-distribution of proteins and architecture of organelles/cells and (iv) faring poorly on probabilistic/evolutionary scales- were clearly brought forth. Although the leading majority of the bioenergetics community remain recalcitrant, it is a matter of foregone conclusion that the ETC-CRAS proposal is fundamentally flawed. This is evidenced by the plummeting drop in usage of terms such as ‘proton motive force’ and ‘chemiosmosis’ in scientific literature [Manoj, 2022]. The most crucial and unassailable fact which we pointed out was that mitochondria and chloroplasts are practically aprotic organelles. These micron-dimensioned and lipid invaginated organelles with packed components have very low amounts of water to dissociate and provide any significant free protons for pumping; and it is thermodynamically unviable that water dissociates to give protons for this purpose (free energy change for the heterolytic dissociation of water is >79 kJ/mole). This irrefutable reality renders the proton-centric chemiosmotic bioenergetics view redundant (Manoj, 2018a). The most salient aspect of the classical view of cellular functioning is that the main protagonists, proteins, act with their diverse

target molecules at a defined active site, going via a transition state (involving a topological complementation of the protein bound with its target molecule), finally to form the products in fixed stoichiometry. The ion-pumping and high-throughput channel theories postulated that ions and various molecules are specifically and selectively acted upon by proteins and therefore, the concentrations of various components and their interactions thereof were maintained as a rather deterministic outcome, based on the “will” of membrane-embedded proteins (in particular!). This mechanistic view is graphically depicted in Figure 1. Under this purview, the “intelligence and regulation” by central dogma is enough to assure that the cells would produce a bunch of proteins, whose active sites would dictate the outcomes of cellular PCHEMS.

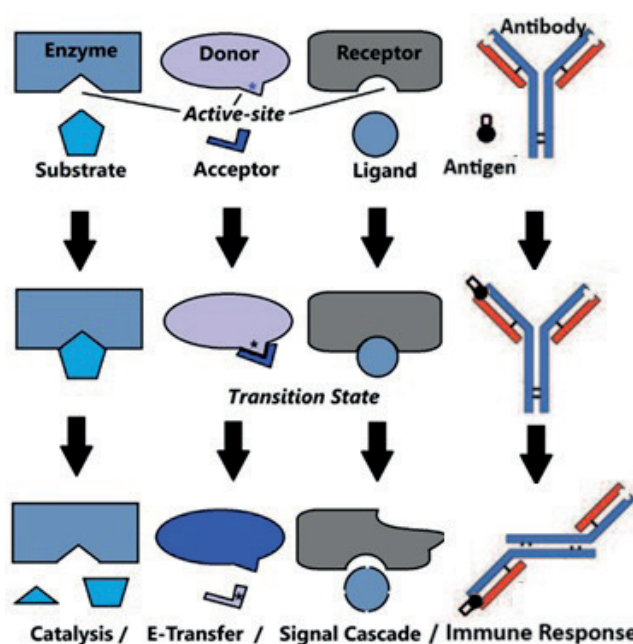


Figure 1. The classical view of protein-mediated function in biology invokes the topologically complementary binding of target molecules to a specific/unique active site on the protein, to stoichiometrically and deterministically give rise to product(s), going via a ‘transition state’ complex.

III. THE ADVENT OF MURBURN CONCEPT, AN UMBRELLA OF EXPLANATIONS FOR VARIOUS FACETS OF LIFE

Murburn derives its origin from “mured burning” (a closed but unrestricted redox process), which involves stochastic interactive equilibria of ‘molecules, unbound ions, and radicals/radiations’ (Manoj, 2018b). These interactions may

lead to one or two electron transfers, modification of moieties, phase changes, post-translational alterations of proteins, etc. The umbrella of considerations and explanations based in ‘murburn’ led to the proposal of models for a wide variety of metabolic and physiological processes (Manoj, 2022 gives a chronological listing of publications until 2022; and Manoj et al., 2023a,b gives the developments thereafter). In its essence, murburn concept entails the probabilistic/stochastic involvement of interactions outside “active site”, and therefore, demonstrate promiscuity in “substrate/ligand/partner” preferences and markedly give non-integral and variable stoichiometry. Murburn models are thermodynamically, kinetically, mechanistically and probabilistically robust, also accounting for the structure-distribution correlations with the function of the proteins/biomolecules in milieu. Murburn concept advocates the viability/necessity of spontaneous one-electron equilibria propagating freely in the cells, amongst its components, more so in specific regimes with high amounts of redox active proteins/biomolecules and ions. [This murburn postulation does not deny the existence of well-established active-site/transition-state mediated 2e mechanistic enzymology!] Such murburn perspective affords a new chemoelectrical foundation to understanding biological phenomena, which was hitherto lacking in classical biology (which relied extensively on proteins’ active-site based mechanisms alone!). In essence, murburn concept holds that suitable redox-active biomolecules donate 1-electron in the presence of O_2 inevitably producing $^*O_2^-$ (as the free energy change of this reaction is -250 kJ/mol) and secondary diffusible reactive oxygen species (DROS) with many consequences: (i) The anionic DROS generate effective charge separation (ECS) powering electrophysiological processes. (ii) DROS get engaged in stochastic *in fluid* reactions of diverse nature, including exergonic phosphorylations (e.g., ATP synthesis) and other derivatizations. (iii) DROS interact with water and could rearrange lattice structure around proteins. (iv) The exergonic nature of DROS reactions could produce electromagnetic radiations that may be used in information and energy transport in cells and tissues. So, the comprehensive functioning and “intelligence” of biological systems could be better integrated and explained (particularly at acute time-scales!) with murburn models. Altogether, murburn concept fundamentally revolutionizes our understanding of life, with several applications to be tapped. A significant aspect of murburn theorization is that it is fully compatible with the coacervate or colloidal nature of cellular milieu (unlike the classical treatments which deem cytoplasm as a dilute solution!).

This fundamentally significant reality affords the scope for more efficient and probabilistic theorization/models for real space-mass-time quantitative applications. The murburn perception at the protein interaction level is shown in Figure 2 and the overall systemic level is shown in Figure 3. Herein, stochastic interactions between various molecules, ions and radicals/radiations are also given importance for the maintenance of routine cellular activity. It is to be clearly registered that the cellular functions may not obligatorily seek the formation of a highly conserved topologically complementary transition state between the protein and its target molecule, but the interactions could be mediated via various diffusible reactive species (DRS, formed due to effective charge separation, ECS) [Manoj group’s publications from 2017 to 2024, of which key are listed within the bibliography. This is essential to convince the reader that substantive work has gone into this idea over the last 2.5 decades!]. Murburn purview postulates that the fundamental PCHEMS is simply/directly the straight-forward manifestation of the ECS-CEM-SCE pivot, and results in BI. This perspective does not counter the existence/validity of affinity-based mandates of central dogma, but complements/supplements it at acute timescales. A comparison of manmade artificial and biological (classical & murburn) intelligent systems is given in Table 1.

IV. MURBURN CONCEPT AND ITS POTENTIAL RELEVANCE/APPLICATION IN BIONIC/CYBORG SYSTEMS

Murburn concept’s application potential in bionic-cyborg technology is yet to be demonstrated. At the outset, murburn concept poses high scope/potential for integrating living systems with bionic and cyborg components. As murburn models emphasize how biological processes can be driven by mild radicals and electron flows, it could provide a framework for understanding complex biochemical reactions in ways that might align with artificial cum synthetic systems. Murburn concept-based approaches would focus on low-energy redox processes, DRS/ROS management, and metabolic coherence. It would offer a biologically realistic approach to solving challenges such as energy supply, oxidative stress, and bioelectrical coherence, etc. laying the foundation for the next generation of cyborg technologies. By synchronizing artificial systems with natural physiological processes, murburn principles promise a future where biological and bionic systems function as one cohesive entity. A snapshot of a few possibilities is shown in Figure 4.

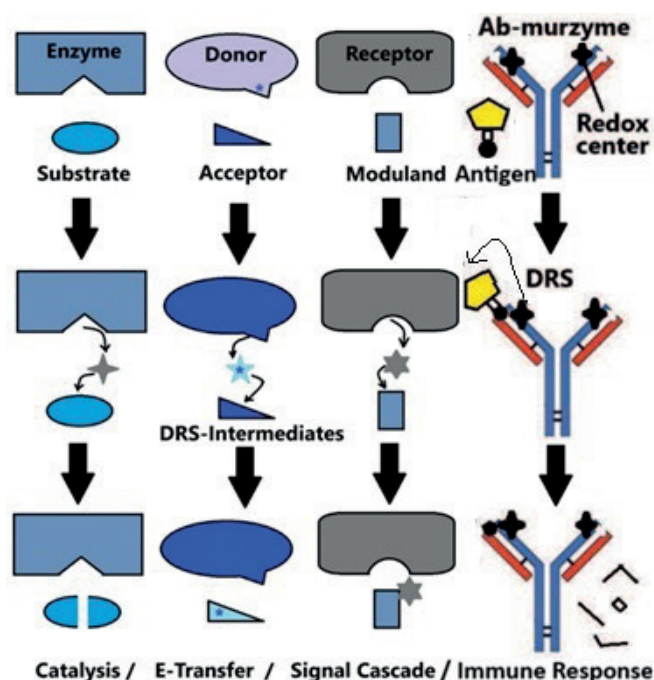


Figure 2. The murburn view is a larger set of interactions (i.e. does not negate the well-evidenced and documented events of Figure 1), invoking the intermediary formation of DRS via ECS. Herein, there could be some binding of low or high affinity between the enzyme and target molecule, but there is uncertainty in the location of reaction and stoichiometry of product formation, owing to the DRS being mobile and its ability to enter into interactive equilibrium with diverse components of the milieu.

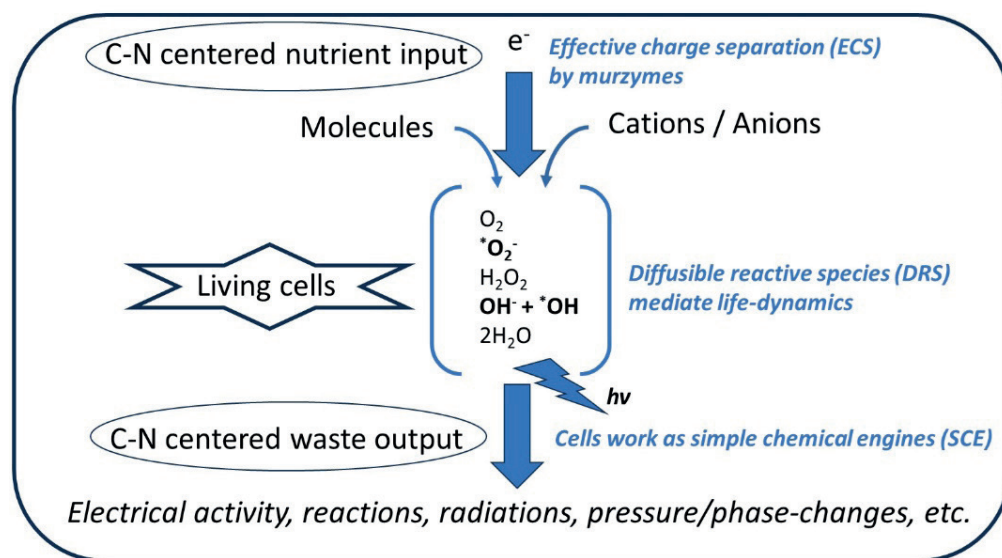


Figure 3. The basic systemic chemico-physical theorization logic of murburn concept for life involves the oxygen-water redox equilibrium as the crux, which is influenced by diverse molecules, ions and electron-donors/acceptors in milieu. This also makes the system sensitive and responsive to ambient chemical, thermal, electrical, pressure, radiations, etc. features. As the underlying principles of murburn concept in life-systems is essentially the same as simple chemical systems, it would be facile to integrate man-made components with life-systems.

Table 1: A comparison of the fundamental differences among the perceptions on intelligences of man-made and biological (both classical and murburn) systems.

	Criteria	Man-made AI	Classical BI	Murburn BI
1	Constitution and components	Ordered networks and gates of passive (conductors/resistors, capacitors, inductors, memristors, etc.) and active (transistors, ICs, processors, etc.) parts, memory devices (RAM/ROM), sensors and actuators, communication and powering modules, etc.	Deterministically placed “intelligent proteins on membranes” serve as sentinel and sentient entities, controlling the flux of cations in and out of the cell	Networks of interactive molecules, ions, radicals and radiations that constitute a cell (and its immediate environment)
2	Nature of electrical activity	Electronic	Ionic (2e stabilized species)	Electronic/ionic (both 1e and 2e active species)
3	Operational principle for electrical activity	Internal manipulation of voltage in loci/bins	Circular logic: Membrane-embedded proteins (MEP_ generate and regulate Trans-membrane potential (TMP) and TMP controls MEPS!	Directional logic: Oxygen comes in and induces ECS-DRS dynamics!
4	Origin of intelligence (decision-making ability in real dimensions of space-mass-time)	Emerges from an interfaced labyrinth of hardware and software, derived by external electrical input.	Resides in molecules (membrane-embedded protein pumps and channels), organelles (nucleus), and organs (brain)	Emerges from interactive e-transfer networks of molecules, ions, radicals, and radiations
5	Fundamental powering	External voltage provision is a must	Internal Electron Transport Chain proteins pump protons across membrane, generating trans-membrane potential (TMP) and Proton Motive Force (pmf).	Internal Effective Charge Separation (ECS) by proteins (taking electrons from nutrients) with oxygen serving as mobile acceptor generates discretized electromotive force (EMF) and TMP is a consequence.
6	Dependence on electrical activity	Electrical activity is input and required for intelligence	Electrical activity is the causative for intelligence	Electrical activity is an outcome of intelligence and not its cause!
7	Self-maintenance and goals	Maintenance depends on external electrical input; goals written in the driving logic	Self-maintenance by auto-powering; Goals written in the DNA-RNA code	Auto-powered systems that can evolve spontaneously owing to stochasticity
8	Overall	Abides by laws of physics	Vital determinism bypasses laws of physics	Abides by laws of physics

A. Energy-transfer/efficiency and compatibility in hybrid systems; biocompatible power source for implants.

Cyborg systems need efficient methods to integrate biological and synthetic elements, especially for energy transfer between components. Murburn concept emphasizes electron flow through one-electron radical-ion networks, which could mimic the natural bioenergetics of cells, such as oxidative phosphorylation by means of simple (chemical) exergonic ROS-dependent ATP-synthesis. Therefore, artificial components could use mild and unrestricted radical-ion systems to bridge energy/continuity gaps between biological tissues and bionic electronics. This could support the development of hybrid cells (with artificial membranes or sensors) that exchange energy seamlessly with electrical circuits or batteries.

A salient use-case scenario would be wearable or implantable devices that scavenge energy from metabolic pathways (e.g., glucose oxidation or oxygen reduction) without disrupting natural processes. When the goal is to utilize the body’s own biochemical redox reactions to power implants, neural prosthetics, or biosensors, murburn systems could provide solutions as they rely on mild redox reactions that could harvest metabolic energy from oxygen and ROS without disrupting cellular processes. Thus, we could develop self-sustaining implants (such as pacemakers or cochlear implants) that are powered by locally generated redox cycles. We could also design microbial fuel cells embedded in tissues for continuous, biocompatible energy production. Artificial systems in cyborgs and bionic organisms often face challenges related to oxygen management for energy production. Also, cellular

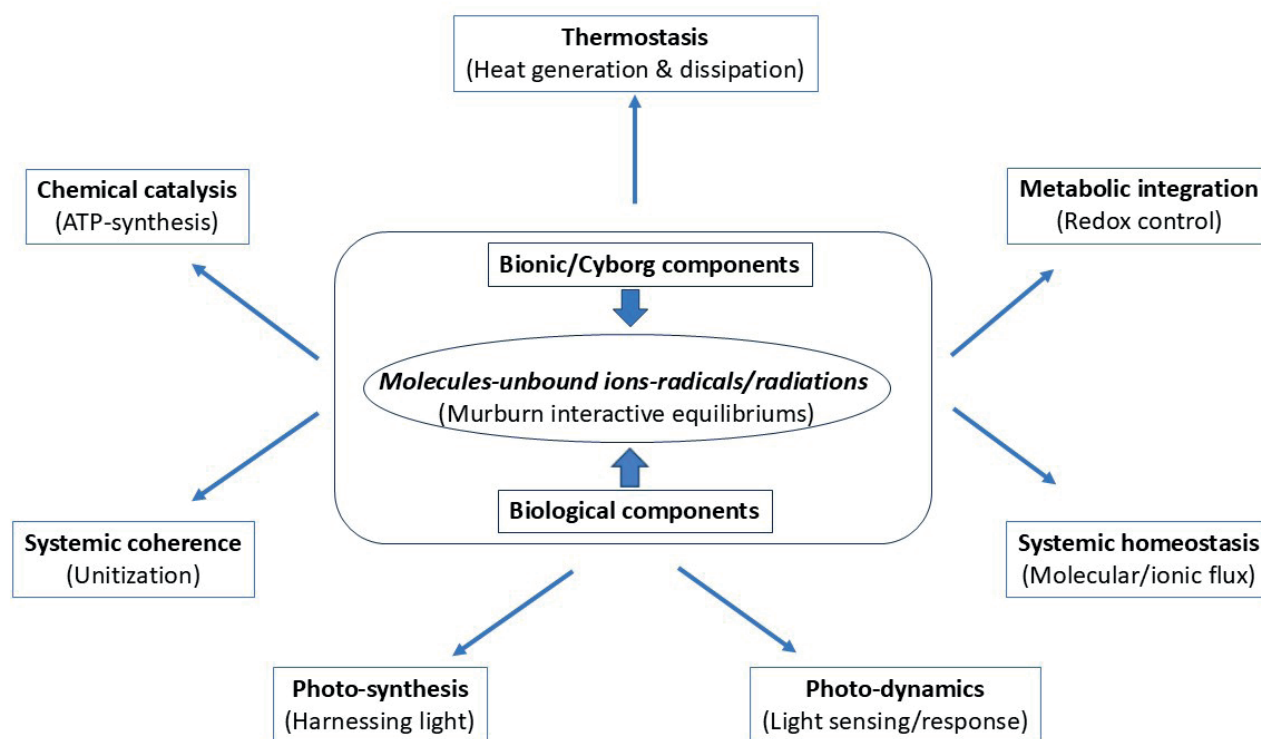


Figure 4. The depiction of diverse domains where murburn concept could mediate/interface the interaction between bionic/cyborg and biological components.

powering is a significant challenge for long-term bio-hybrid systems, such as bioengineered tissues or cyborg components. Murburn-based processes highlight efficient oxygen management through mild radical production and electron transport, akin to cellular respiration. This could lead to the development of artificial mitochondria or bio-hybrid power sources for bionic systems. Therefore, a use-case scenario would be in artificial organs or wearable devices that harvest oxygen from bloodstreams to generate electricity for powering embedded electronics. Murzymes (oxidases, peroxidases, etc.) under murburn models can facilitate mild oxidative reactions, producing ATP-equivalents or metabolic energy by using small ROS molecules like H_2O_2 and superoxide. These reactions could mimic natural mitochondria, providing localized power sources for lab-grown tissues, synthetic organs, or bionic implants. Such efforts could help design artificial mitochondria-inspired “batteries” inside tissue-engineered organs or neuro-implants, powering them continuously with the body’s natural oxygen flux. Murburn reactions describe a way in which electron transfer occurs using oxygen, without requiring large energy inputs. Bionic and cyborg systems, especially those that interface with living tissues, could benefit

from integrating this principle by mimicking nature’s energy-efficient ways of transferring electrons and handling metabolic processes. This could allow for more effective powering of bionic components using biological energy sources, improving longevity and integration without heavy reliance on external power.

B. Integrative thermoregulation and miscellaneous radiation-based energization/exchange amongst biological and cyborg components

Murburn concept provides a thermodynamically viable explanation for thermogenesis in mitochondria [Manoj’s eLetters to Science/Science Advances in 2023]. The ability to generate and dissipate heat is vital for both biological and artificial systems. Bionic technologies that incorporate principles from murburn concept can improve thermal management, ensuring that devices do not overheat and can function optimally within the biological/ambient environment. Also, thermal energy-based changes and transductions (for both fuelling/energizing and sensory effects) can be achieved.

Murburn concept is the fundamental phenomenological explanation for photosynthesis, photoreception and photody-

namic effects in physiology [Manoj group's publications in photosynthesis, as listed in Manoj 2022]. Based on the new know-how, futuristic technologies could incorporate sun-light-tapping panels integrated into bionic-animal systems for providing alternative energetic sources. Photo-sensitive arrays based in murburn concept could also enable light-guided sensing-response options for bionic systems. Also, such radiation-based interactions of components could be used to bring about synergy and coherence within the bionic/cyborg systems. A comprehensive interactive network of high and low energy radiations and DRS networks (the murburn-EM matrix) was recently proposed [Jaeken & Manoj, 2025].

C. Electrophysiological “sensing-response” connectivity for communication between biological and synthetic components

For successful integration of living systems and bionic components, the need to effectively interface them and get them to communicate seamlessly at a biochemical level may be required. Murburn concept endorses that low concentrations of radicals-ion network relays can modulate signalling and metabolic pathways without causing damage. Synthetic components could generate controlled one-electron signals that biological systems naturally respond to. This approach could bridge the gap between neural signals and artificial sensors or actuators, improving the performance of prosthetics and brain-machine interfaces. Murburn-based chemistry may also facilitate the coupling of biosensors to physiological pathways without excessive interference. A typical application would be incorporating murburn-like radical processes into neural implants to fine-tune synaptic signals, enhancing real-time interaction between the brain and artificial limbs. When we would seek to improve the interaction between neuronal or muscular tissues and bionic devices, we could attempt it by leveraging murburn reactions to stabilize electrical signals. Murburn concept explains mild, stochastic fluctuations in electrophysiology that maintain coherence in ion channels, synapses, and nerves. Thus, we could create adaptive neural interfaces that minimize noise by mimicking natural bioelectric rhythms. We could also optimize brain-machine interfaces for smoother signal transduction between neurons and external devices. Murburn reactions are typically seen in electron-transport systems (like cytochromes on endoplasmic reticulum and respiratory complexes in mitochondria) that form the foundation for biochemical electrochemical processes. This knowledge could be used to improve the electrochemical interfaces between biosensors,

actuators, or neural implants and the biological systems they connect with. It provides a model for creating stable redox environments that closely mimic biological electron transfer systems. A major challenge in brain-machine interfaces (BMIs) is maintaining electrical coherence between neurons and artificial electrodes. Fluctuations in bioelectricity can create noise and disrupt signal quality. Awareness of murburn reactions can promote low-level stochastic electron transfers, which align with natural, fluctuating ion channel activities seen in neurons. These principles can be applied to adaptive electrodes that behave like neurons by maintaining dynamic signal coherence through redox balancing. Neural implants for paralysis patients or memory-enhancing chips could use murburn-based electrode systems to ensure smooth, noise-free communication between neurons and machines.

D. Reduced complexity in biochemical pathways for integration, minimizing oxidative stress and integrating/synchronizing biological-artificial redox metabolisms

Murburn concept emphasizes parsimonious and parallel reaction pathways, which makes complex biochemical systems easier to model and control. Such simplified approach could help model metabolic processes and simulate how bio-electronic interfaces interact with tissues. By understanding energy flows and signalling with minimal steps, artificial components can operate in tandem with natural ones without causing disruptions. A simple application would be in cyborg devices using murburn models to mimic enzyme activity and support organ regeneration or tissue healing by supplementing failing biochemical functions. Also, when the goal is to manage the build-up of DRS/ROS at the interface of biological tissues and synthetic implants (to prevent inflammation, degradation and rejection), an advanced awareness of murburn principles/strategies could buffer ROS levels through controlled redox reactions, mimicking natural biochemical regulation and immune profiles/properties. Such strategies could help design anti-oxidative surfaces on implants to reduce oxidative damage and enable ROS-regulating coatings in bionic limbs and organs for improved biocompatibility and longevity. When we seek to synchronize/integrate biological and artificial metabolisms for greater harmony, murburn based approach could allow for seamless interactions that also streamlines energy/material flows. These could aid in artificial tissue and organ development (biohybrid kidneys, say!) that work in tandem with native organs by tapping into shared energy resources, sustaining redox balance.

Cardiac pacemakers or retinal implants with murzyme-based protective layers could enhance biocompatibility, improving patient outcomes over long-term usage. We could also build bio-compatible synthetic muscles that interface with body's metabolic process for powered movement.

E. Miscellaneous redox-activity based bioelectronic sensor systems, soft robotics for biomedical applications, neuro-prosthetics, and artificial nerve networks

Murburn models could aid develop implantable biosensors that can detect biochemical changes with high sensitivity and low power consumption. Murburn principles could be used to drive electron transfers and signal processing directly within the body's redox environment. The implanted sensors could be used for continuous monitoring of key redox active metabolites or oxygen sensing in critical care patients. It could be used to build adaptive, real-time feedback systems in robotic limbs or wearable medical devices to respond to biological signals. This could also fuel the development of long-lasting bioelectronic devices (e.g., pacemakers or brain implants) that release/uptake mild radicals or alter one-electron equilibriums to maintain tissue health while preventing scarring or inflammation. This is particularly useful for implanted sensors and electrodes, where long-term biocompatibility is critical. We could incorporate mild redox-based energy flows into soft robotics for enhanced flexibility and adaptability in medical devices. We could leverage murburn reactions for local energy generation and controlled chemical signalling in soft, bio-compatible robots. At one hand, these could aid develop soft exoskeletons that interface with the body's redox systems for powered motion and could at the other hand, also help build surgical robots with real-time biofeedback, reducing stress on tissues during procedures. Murburn systems would allow for distributed, low-energy redox-driven reactions, similar to the way natural muscles operate through mild oxidative bursts. Redox-active murzymes could act as energy converters within hybrid muscles, facilitating smoother transitions between rest and contraction states. Cyborg muscles or exoskeleton suits that leverage murburn principles for real-time adaptive control during walking or heavy lifting.

Utilizing murburn principles could allow us to enhance the performance of neuroprosthetic devices by mimicking the natural stochastic redox processes governing nerve excitability. Advanced murburn models for neuronal activity could help to stabilize and facilitate smooth neural communication. Futuristic efforts to design artificial nerve networks

for spinal cord repair and sensory restoration could be aided by incorporating murburn concept-based ideas. This could also aid the development of cybernetic neural implants for people with motor disabilities, allowing intuitive control over external devices. Rebuilding damaged nerves or designing artificial ones to restore sensory functions in amputees requires stable bioelectrical signalling. Murburn principles could optimize signal transduction across artificial nerve networks by ensuring a balance of DRS equilibriums. Prosthetic limbs with murburn-based sensors could fashion and adjust grip strength based on detected muscle fatigue or stress levels.

V. SPECIFIC CONTEXTS AND EXAMPLES OF HOW MURBURN CONCEPT COULD FASHION ANALOG TO DIGITAL (A/D) CONVERSIONS IN BIONIC/CY-BORG SYSTEMS

Classical and common protein-ligand binding based phenomena are typically understood as unidirectional process, i.e. more ligand or more protein present correspondingly gives rise to greater transition-state bound species, which, in turn, gets translated downstream into a greater analog signal. This may get attenuated at higher concentration levels of the ligand, in which case we might observe a saturation of the signal. However, life processes are sometimes characterized by zeroth order reactions (even into micromolar ranges) and threshold-based “all or none” type responses. These can result as an outcome of murburn chemistry. The following are some potential areas where such murburn processes could be harnessed for analog-digital conversions.

A. Encoding biological stochasticity into digital signals

Biological processes, especially in neurons and ion channels, exhibit stochastic behaviour, wherein small, random fluctuations in chemical and electrical states contribute to activity. Murburn reactions align with these natural fluctuations by allowing distributed, low-energy electron transfers and redox reactions. Murburn models could provide a bridge between noisy, analog biological fluctuations (e.g., ion flow through channels) and digital logic gates. Specialized biosensors with murzyme-inspired coatings could detect subtle analog changes in ionic flux, pH, or redox state and translate them into current/voltage pulses that correspond to binary values (0s and 1s). In neuro-prosthetics: A brain-machine interface (BMI) could translate stochastic bursts of neural activity into discrete digital signals for controlling robotic arms or

exoskeletons. When a muscle neuron fires with low, irregular ionic fluctuations, murburn-inspired systems could normalize and integrate the noise into consistent, digitizable current/voltage surges/spikes.

B. Threshold-based A/D conversion based on redox gradients

Biological systems often exhibit chemical gradients and redox activity to fashion biochemical sensing/response. In murburn models, small molecules like oxygen and peroxide (and their redox products thereof) modulate reactions at specific concentration thresholds. Redox thresholds could act as analog inputs that trigger digital outputs- for example, when the redox potential exceeds a certain level, the system outputs a “1”, otherwise, it remains “0”. This could be based on cell geometry and other local interactive equilibrium features. Murzyme systems can tune redox fluxes dynamically, thereby functioning as analog sensors with specific thresholds for generating binary responses. When blood glucose reaches a critical threshold, a murburn-based biosensor could generate a digital signal to trigger insulin pumps or cardiac pacing interventions.

C. Time-based signal processing and frequency encoding of redox bursts

In murburn-driven reactions, electron transfer occurs in a time-dependent, non-linear fashion. Similarly, neurons rely on temporal patterns (e.g., spike trains) to encode information. Murburn principles can help match these time-based analog patterns to digital systems. We could use modelled frequency-modulated redox bursts to encode biological signals for digital conversion. A burst of ROS or electron transfer can correspond to a binary sequence, such as a spike train translated into current or voltage pulses. Time-varying redox currents can act as analog inputs that are quantized into discrete pulses for digital processing. In cochlear implants, sound waves captured by the ear generate graded electrical potentials. Murburn-inspired redox modules could convert these potentials into digitized signals, improving sound clarity and enabling fine-tuned neural stimulation.

D. Multi-sensor networks for distributed A/D conversion

Murburn reactions allow distributed and parallel electron transfers, which are similar to multi-channel sensory networks in biological systems. This distributed nature can facilitate multi-point A/D conversions for complex systems,

such as the simultaneous recording of neural signals from different regions. Multiple murzyme-based sensors can simultaneously monitor various biochemical signals (e.g., pH, redox potential, oxygen levels) and convert these into parallel digital outputs. Each redox change in the system corresponds to a unique binary code, enabling the translation of multi-dimensional analog inputs into digital datasets for processing by artificial components. For developing full-body robotic prosthetics, distributed sensors along the skin or muscles can capture localized metabolic signals (e.g., lactate build-up or oxygenation) and convert them into real-time digital feedback for the prosthetic limb.

E. Adaptive A/D converters in cyborg implants using murburn feedback loops

Murburn systems inherently support dynamic feedback loops, by virtue of the 1e (unstable) to 2e (stable) cycling logic. These loops could help calibrate A/D conversions in real-time by adapting to changes in the biological environment (e.g., fluctuating metabolic activity). Adaptive redox circuits that dynamically adjust their threshold levels based on feedback from biological systems could be used. This would ensure that the A/D conversion remains stable even when the biological input fluctuates due to fatigue or stress. The feedback loop allows for real-time recalibration of the A/D conversion, ensuring smooth and consistent signal transfer. Adaptive A/D converters in smart wearables (like blood oxygen monitors) could adjust their sensitivity to avoid false readings under different physiological conditions, such as physical exercise or sleep.

F. Digital control of redox-based biohybrid actuators

In some bionic systems, digital signals would be needed to trigger biohybrid actuators (e.g., artificial muscles) powered by biochemical reactions. Murburn-driven reactions can serve as bio-electrochemical switches that respond to digital inputs. Digital input signals (0 or 1) can control the initiation or cessation of murburn-based redox cycles, which then drive biochemical actuators. For instance, a digital pulse from a brain-machine interface could activate localized ROS production, triggering the contraction of a synthetic muscle. Binary inputs from neural signals could control bio-electronic actuators for walking or lifting, allowing real-time interaction between the biological nervous system and robotic components.

VI. SUMMATIVE STATEMENTS

The classical membrane electrogenic ion-pumps and high-

throughput channel proposal stands totally discredited and refuted beyond redemption (Manoj et al., 2025a). Murburn concept is a fully mathematically grounded theory now, consolidated with equations for organellar/cellular TMP (Manoj et al., 2025b) and murzyme-mediated biological electron transfer (BET) and catalysis (Manoj, 2025). Further, murburn’s role in post-translational modifications (Manoj, 2024a) and immunological integrations have been established (Manoj, 2024b). Our efforts to algorithmically classify enzymes mechanistically and with AI-assisted training into classical or murburn systems have also met with success (unpublished work, to be released soon; part of which is available at: <https://shark-app-tly4j.ondigitalocean.app/>). Such developments offer exciting new opportunities for modeling, predicting and directly interfacing man-made artificial components with biological systems.

Murburn concept offers a thermodynamically and kinetically facile “molecule-ion-radical/radiation interaction” that explains the acute necessity of oxygen for sustaining life and provides a framework for seamlessly integrating living systems with bionic and cyborg components. By leveraging mild one-electron transfers and radical reactions (and or their interactive scheme with radiations), it is feasible to derive simplified electron transport, and bio-compatible energy flows. This facet could help solve challenges related to energy management, signal integration, and long-term biocompatibility. In the future, murburn-based chemistry could lead to new forms of biohybrid systems that operate seamlessly with natural biology, revolutionizing areas such as neural interfaces, prosthetics, and implantable medical devices. Incorporating murburn principles into cyborg and bionic systems could allow for better energy management, lower oxidative stress, and improved electrochemical integration. These benefits could enable more sustainable, compatible, and efficient merging of living tissues with artificial components, pushing forward the possibilities in the fields of bioengineering, medical devices, and synthetic biology. From self-powered implants to adaptive prosthetics, the stochastic, redox-driven processes central to murburn principles align closely with the dynamic nature of living systems. As cyborg research evolves, murburn-based approaches will likely play a pivotal role in designing self-regulating, energy-efficient, and metabolically coherent devices that seamlessly integrate with human physiology. Murburn concept could offer an elegant solution for analog-to-digital (A/D) conversions by leveraging the natural stochasticity, threshold responses, and time-

based signalling found in biological systems. It may provide a robust framework for matching continuous, noisy biological inputs with the discrete digital outputs required by bionic and cyborg devices. Through threshold-based redox sensing, frequency modulation, distributed sensor networks, and adaptive feedback, murburn principles could enable seamless communication between living tissues and artificial components, paving the way for the next generation of cyborg technologies. As of now, the reluctance in the leadership of scientific community to recognize murburn concept as a fundamental biochemical logic is the main barricade preventing the application of the new idea in diverse fields. With the advent of time, greater acceptability for murburn concept would pave the way for its application in bionic-cyborg technology.

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REFERENCES

1. Alberts B, Johnson A, Lewis J, Raff M, Roberts K, & Walter P. (2008). *Molecular biology of the cell* (5th edn.). Garland Science.
2. Berg JM, Tymoczko JL, & Stryer L. (2002). *Biochemistry* (5th edn.). WH Freeman.
3. Clark A. (2003). *Natural-Born Cyborgs: Minds, Technologies, and the Future of Human Intelligence*; Oxford University Press, ISBN: 0-1951-4866-5.
4. Gideon, D. A., Annadurai, P., Parashar, A., & Manoj, K. M. (2024) Re-interpretation of structure-function correlations and inhibitions of mammalian cyclooxygenase isozymes with murburn concept. *Biomedical Reviews* 35, 71-113.
5. Jaeken L & Manoj KM. (2025) Murburn Bioenergetics and “Origins–Sustenance–Termination–Evolution of Life”: Emergence of Intelligence from a Network of Molecules, Unbound Ions, Radicals and Radiations. *International Journal of Molecular Sciences* 26, 15 (7542).
6. Kelly K. (1994). *Out of Control: The New Biology of Machines, Social Systems, and the Economic World*. Basic Books. ISBN-10 : 0201483408
7. Manoj KM & Jaeken L (2023) Synthesis of theories on cellular powering, coherence, homeostasis and electromechanics: Murburn concept & evolutionary perspectives. *Journal of Cellular Physiology* 238, 931. doi: 10.1002/jcp.31000

8. Manoj KM (2022) Murburn concept and murzymes in 2023: Celebrating 25th year of pursuit. *Biomedical Reviews* 33, 1-15. doi: 10.14748/bmr.v33.9115.
9. Manoj KM and Bazhin NM (2021). The murburn precepts for aerobic respiration and homeostasis. *Progress in Biophysics and Molecular Biology* 167: 104-120. doi: 10.1016/j.pbiomolbio.2021.05.010
10. Manoj KM and Soman V. (2020). Classical and murburn explanations for acute toxicity of cyanide in aerobic respiration: A personal perspective. *Toxicology* 432: 152369. doi: 10.1016/j.tox.2020.152369
11. Manoj KM et al. (2023a) Murburn concept in cellular function and bioenergetics, Part 1: Understanding murzymes at the molecular level. *AIP Advances* 2023;13(12) id.120702, 22pp. doi: 10.1063/5.0171857.
12. Manoj KM et al. (2023b) Murburn concept in cellular function and bioenergetics, Part 2: Understanding integrations-translations from molecular to macroscopic levels. *AIP Advances* 13(12) id.120701, 23pp. doi: 10.1063/5.0171860
13. Manoj KM, Bazhin NM, Tamagawa H. (2021). The murburn precepts for cellular ionic homeostasis and electrophysiology. *Journal of Cellular Physiology* 237: 804-814.
14. Manoj KM, Bazhin NM, Tamagawa H., Jaeken L, Parashar A. (2022). The physiological role of complex V in ATP synthesis: Murzyme functioning is viable whereas rotary conformation change model is untenable. *Journal of Biomolecular Structure and Dynamics*. 41 (9), 3993-4012 doi: 10.1080/07391102.2022.2060307.
15. Manoj KM, Gideon DA, & Jaeken L. (2022) Why do cells need oxygen? Insights from mitochondrial composition and function. *Cell Biology International* 46:344-358. doi: 10.1002/cbin.11746
16. Manoj KM, Gideon DA, and Jacob VD. (2018). Murburn scheme for mitochondrial thermogenesis. *Biomedical Reviews* 29: 73-82.
17. Manoj KM, Gideon DA, Bazhin NM, Tamagawa H, Nirusimhan V, Kavdia M, Jaeken L. (2023). Na,K-ATPase: A murzyme facilitating thermodynamic equilibriums at the membrane-interface. *Journal of Cellular Physiology*. 238(1):109-136. doi: 10.1002/jcp.30925
18. Manoj KM, Gideon DA. (2022) Structural foundations for explaining the physiological roles of murzymes embedded in diverse phospholipid membranes. *Biochimica et Biophysica Acta Biomembranes*.1864(10):183981. doi: 10.1016/j.bbamem.2022.183981.
19. Manoj KM, Nirusimhan V, Parashar A, Edward J, Gideon DA. (2022). Murburn precepts for lactic-acidosis, Cori cycle, and Warburg effect: Interactive dynamics of dehydrogenases, protons, and oxygen. *Journal of Cellular Physiology* 237:1902–1922. doi: 10.1002/jcp.30661
20. Manoj KM, Parashar A, David Jacob V, and Ramasamy S. (2019). Aerobic respiration: proof of concept for the oxygen-centric murburn perspective. *Journal of Biomolecular Structure and Dynamics* 37: 4542-4556. doi: 10.1080/07391102.2018.1552896
21. Manoj KM, Ramasamy S, Parashar A, Gideon DA, Soman V, Jacob VD, Pakshirajan K. (2020) Acute toxicity of cyanide in aerobic respiration: Theoretical and experimental support for murburn explanation. *Biomolecular Concepts*. 11(1):32-56. doi: 10.1515/bmc-2020-0004.
22. Manoj KM, Soman V, David Jacob V, Parashar A, Gideon DA, Kumar M, Manekkathodi A, Ramasamy S, Pakshirajan K, and Bazhin NM. (2019). Chemiosmotic and murburn explanations for aerobic respiration: Predictive capabilities, structure-function correlations and chemico-physical logic. *Archives of Biochemistry and Biophysics* 676: 108128. doi: 10.1016/j.abb.2019.108128
23. Manoj KM, Tamagawa H, Bazhin N, Jaeken L, Nirusimhan V, Faraci F, Gideon DA. (2022). Murburn model of vision: Precepts and proof of concept. *Journal of Cellular Physiology* 237: 3338-3355.
24. Manoj KM, Tamagawa H. (2021). Critical analysis of the explanations for cellular homeostasis and electrophysiology from murburn perspective. *Journal of Cellular Physiology* 237:421-435.
25. Manoj KM. (2017) Debunking chemiosmosis and proposing murburn concept as the operative principle for cellular respiration. *Biomedical Reviews* 28, 31-48. doi: 10.14748/bmr.v28.4450
26. Manoj KM. (2018a). Aerobic Respiration: Criticism of the proton-centric explanation involving rotary adenosine triphosphate synthesis, chemiosmosis principle, proton pumps and electron transport chain. *Biochemistry Insights* 11: 1178626418818442.
27. Manoj KM. (2018b). The ubiquitous biochemical logic of murburn concept. *Biomedical Reviews* 29: 89-97. doi: 10.14748/bmr.v29.5854

28. Manoj KM. (2020) Refutation of the cation-centric torsional ATP synthesis model and advocating murburn scheme for mitochondrial oxidative phosphorylation. *Biophysical Chemistry*. 257:106278. doi: 10.1016/j.bpc.2019.106278.
29. Manoj KM. (2020). In defense of the murburn explanation for aerobic respiration. *Biomedical Reviews* 31:135-160. doi: 10.14748/bmr.v31.7713 (Refer also the pertinent Supplementary Information file)
30. Manoj KM. (2020). Murburn concept: a paradigm shift in cellular metabolism and physiology. *Biomolecular Concepts* 11: 7-22. doi: 10.1515/bmc-2020-0002
31. Manoj KM. (2023) Murburn concept provides a thermodynamically valid and kinetically facile oxygen-centric explanation for mitochondrial heat generation. (eLetter) *Science*. doi: 10.1126/science.abl7108
32. Manoj KM. (2023) The murburn rationale for phosphatidylethanolamine's modulation of UCP1 mediated thermogenesis. (eLetter) *Science Advances*. doi: 10.1126/sciadv.ade7864
33. Manoj KM. (2024a) Murburn posttranslational modifications of proteins: Cellular redox processes and murzyme-mediated metabolo-proteomics. *Journal of Cellular Physiology*. doi:10.1002/jcp.30954
34. Manoj, KM. Gideon DA, Samuel PM, Das S (2025). Quantitative treatments for explaining the mechanism and kinetics of catalytic electron-transfers in murburn processes, particularly involving heme-enzymes like per(oxidases) and P450s. *Biomed Research International*.
35. Manoj, K. M., Jaeken, L., Gideon, D. A., Tamagawa, H., & Kavdia, M. (2025b, February 13). Murburn theorization for cellular/organellar trans-membrane potential. *OSF Preprints*. doi: 10.31219/osf.io/mn72q_v4
36. Manoj, K. M. (2024b) Murburn concept and biological intelligence at the cusp of 2025: Sensitivity to sensibility, sensuality to sexuality, cybernetics to cyborg-bionics, and more! *Biomedical Reviews*, 35, 1-27.
37. Manoj, K. M., Gideon, D. A (2024) Consolidation of the murburn model of flagella-aided motility in bacteria. *Biomedical Reviews*, 35, 39-70.
38. Manoj, K. M., Jaeken, L., Gideon, D. A., Tamagawa, H., & Kavdia, M. (2025a, April 18). A critical perspective on the foundations of cellular electrophysiology. *OSF Preprints*. https://doi.org/10.31219/osf.io/4kexv_v1
39. Nelson DL, & Cox MC. (2004). *Lehninger: Principles of biochemistry* (4th edn.). W H Freeman.
40. Penketh P. (2022) Is DNA repair controlled by a biological circuit? *Theory in Biosciences* 141, 41-47. doi: 10.1007/s12064-021-00360-8
41. Penketh P. (2023) Is the cell a digitally controlled system, *NanoIntellects* September, Berlin, doi:10.13140/RG.2.2.21483.31527
42. Shi, Z., Ma, G., Wang, S., Li, J. (2016). Brain-Machine Collaboration for Cyborg Intelligence. In: Shi, Z., Vadera, S., Li, G. (eds) *Intelligent Information Processing VIII. IIP 2016. IFIP Advances in Information and Communication Technology*, vol 486. Springer, Cham. https://doi.org/10.1007/978-3-319-48390-0_26
43. Talanov M, Vallverdu J, Adamatzky A, et al., & Warwick K (2022). Neuropunk Revolution. Hacking Cognitive Systems towards Cyborgs 3.0. arXiv preprints. <https://arxiv.org/abs/2205.06538v1>
44. Voet D, & Voet JG. (2011). *Biochemistry* (4th edn.). Wiley.
45. Warwick, K. (2002). *I, Cyborg*. Century Press. ISBN-10 : 0712669884
46. Wiener, N. (1948). *Cybernetics: Or Control and Communication in the Animal and the Machine*. MIT Press.
47. Wu Z, Reddy R, Pan G, Zheng N, Verschure PFMJ, Zhang Q. The Convergence of Machine and Biological Intelligence (2013) *IEEE Intelligent Systems*, vol. 28, no. 5, pp. 28-43, Sept.-Oct. 2013, doi: 10.1109/MIS.2013.137.
48. Wu Z, Zhou Y, Shi Z, Zhang C, Li G, Zheng X (2016). Cyborg Intelligence: Recent Progress and Future Directions. *IEEE Intelligent Systems*, vol. 31, no. 6, pp. 44-50, Nov.-Dec. 2016, doi: 10.1109/MIS.2016.105.