



Pei Liu

Department of Mechanical Engineering,
Rice University,
Houston, TX 77005
e-mail: pl53@rice.edu

Chihong Lee

Department of Mechanical Engineering,
Rice University,
Houston, TX 77005;
Department of Civil
and Environmental Engineering,
Rice University,
Houston, TX 77005
e-mail: cl124@rice.edu

Nicole Carusetta

Department of Mechanical Engineering,
Rice University,
Houston, TX 77005
e-mail: ec65@rice.edu

Raudel Avila¹

Department of Mechanical Engineering,
Rice University,
Houston, TX 77005;
Rice Advanced Materials Institute,
Rice University,
Houston, TX 77005;
Digital Health Institute,
Rice University,
Houston, TX 77005
e-mail: ra88@rice.edu

Transient Mechanics: A Perspective on Bioresorbable Electronics

Materials, devices, and systems with the ability to physically disappear create unique opportunities for vanishing electronic technologies in biomedicine. Their transient response, achieved by resorption, degradation, and disintegration, can be carefully programmed through material selection and mechanical design to last from days to weeks when exposed to physiological environments. In this perspective, we examine the mechanics functionality of transient electronics and their diverse applications ranging from compact medical implants to zero-waste environmental hardware. Using a question–answer structure, we highlight the important role of temporary, yet stable, properties for mechanical, electrical, and chemical disintegration over controlled operational lifetimes. Mechanics and electromagnetic strategies are discussed to devise new classes of bioresorbable electronics for the unconventional biomedicine opportunities that can be achieved by vanishing electronic technologies. [DOI: 10.1115/1.4067952]

Keywords: mechanics, materials, constitutive modeling, reaction-diffusion, transient electronics, computational mechanics, elasticity, mechanical properties of materials, micromechanics, structures

Everlasting or Transient?

Rapid and transformative developments of high-performance electronics and integrated systems affect nearly every aspect of design and applications in modern digital technology. Sophisticated integrated circuits with computing and sensing capabilities, packed into miniature form factors, have been successfully adopted across a wide range of fields, from autonomous robotic systems to implantable medical devices. *Everlasting* electronic systems, designed for durability and stability over years or even decades of use, are ubiquitous, with demand continuing to rise as the global population grows. However, this increase presents significant challenges in managing the millions of tons of electronic waste (e-waste) generated annually [1,2]. In contrast, *transient* electronics systems represent a fundamentally different type of emerging technology, designed to have specific lifetimes [3,4]. During use or upon the application of external stimuli, these electronic systems safely

disintegrate into the surrounding environment, either partially or completely, in a controlled and programmed manner [5]. This unique vanishing capability, made possible by various categories of resorbable materials and mechanical designs [6,7], discussed later in this article, is highly desirable for applications in bioelectronic medicine and eco-friendly electronics requiring dynamic mechanical compliance paired with high-performance electronic functionality.

However, as illustrated in Fig. 1, predicting the effective mechanical properties and corresponding structural response of physically transient integrated electronics is nontrivial. These properties are strongly influenced by the diffusion and reaction chemistry of the materials with their surrounding environment [8], particularly since dissolution and operational timescales are nonuniform across multimaterial designs. While the mechanical response of bioresorbable electronics can be readily characterized before dissolution to obtain force–displacement or stress–strain curves, evaluating these mechanical properties *in vivo* during resorption is notoriously challenging—and often impossible—when the structures disintegrate within minutes or hours in biological environments. This implies that the coupling mechanisms between transient kinetics and mechanics in bioresorbable electronics are governed by characteristic length scales, time scales, and

¹Corresponding author.

Contributed by the Applied Mechanics Division of ASME for publication in the JOURNAL OF APPLIED MECHANICS. Manuscript received January 19, 2025; final manuscript received January 22, 2025; published online February 28, 2025. Tech. Editor: Pradeep Sharma.

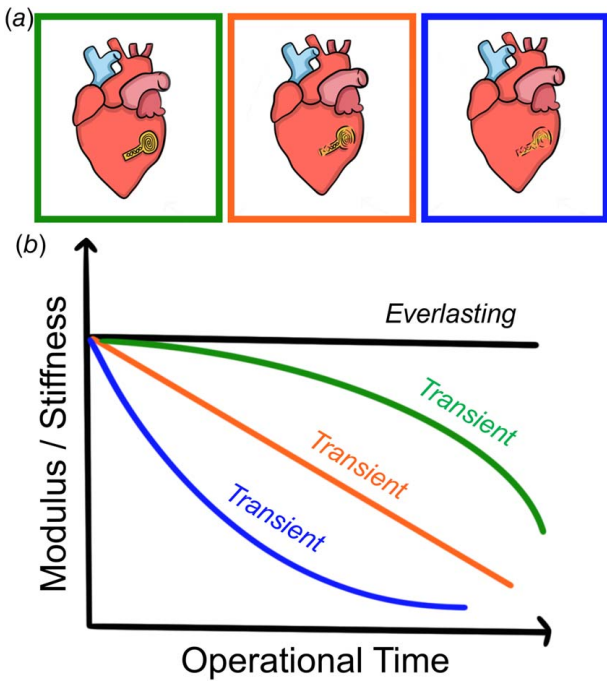


Fig. 1 Bioresorbable electronics in curvilinear surfaces. (a) Illustration of three representative cases of bioresorbable electronic devices undergoing dissolution at different rates. **(b)** Transient mechanical properties (modulus/stiffness) of the representative designs over their operational time.

concentration gradients. Together, these parameters can be optimized to predict and control the structural response, in real time, of new multifunctional systems with transient mechanical capabilities. However, mechanics and materials challenges remain to integrate multiphysics functionality into transient electronic systems while maintaining stability, biocompatibility, and complete resorption within minimal form factors.

What Are Some Examples of Bioresorbable Electronics?

Compact electronic circuits with passive and active components that dissolve in water or biofluids enable applications for temporary technology with minimal to negligible environmental or biological impact [9]. Several works have introduced implantable devices with bioresorbable mechanical, electrical, and chemical subsystems (Fig. 2 highlights different designs, functionalities, and resorption timescales) that support applications in clinical monitoring, stimulation, and drug delivery within the body. These devices incorporate bioresorbable conductors, semiconductors, and encapsulation materials, each with unique mechanical properties and resorbable kinetics. Recent clinical technologies include:

- Cardiac pacemakers [11,13] and patches [10]
- Gastric pH sensors [14]
- Radiofrequency sensors [15–17]
- Temperature sensors [18]
- Nerve stimulators [19–22]
- Neural interfaces [23–26]
- Pressure sensors [27–30]
- Strain sensors [31,32]
- Drug delivery platforms [12,33–36]

Bioresorbable electronics, introduced as an alternative to permanent implants that require extraction surgeries, eliminate the need for such removal procedures and associated risks [11,37,38]. These physically *transient* technologies are designed to be safely assimilated and metabolized by the body [39] in desired timescales

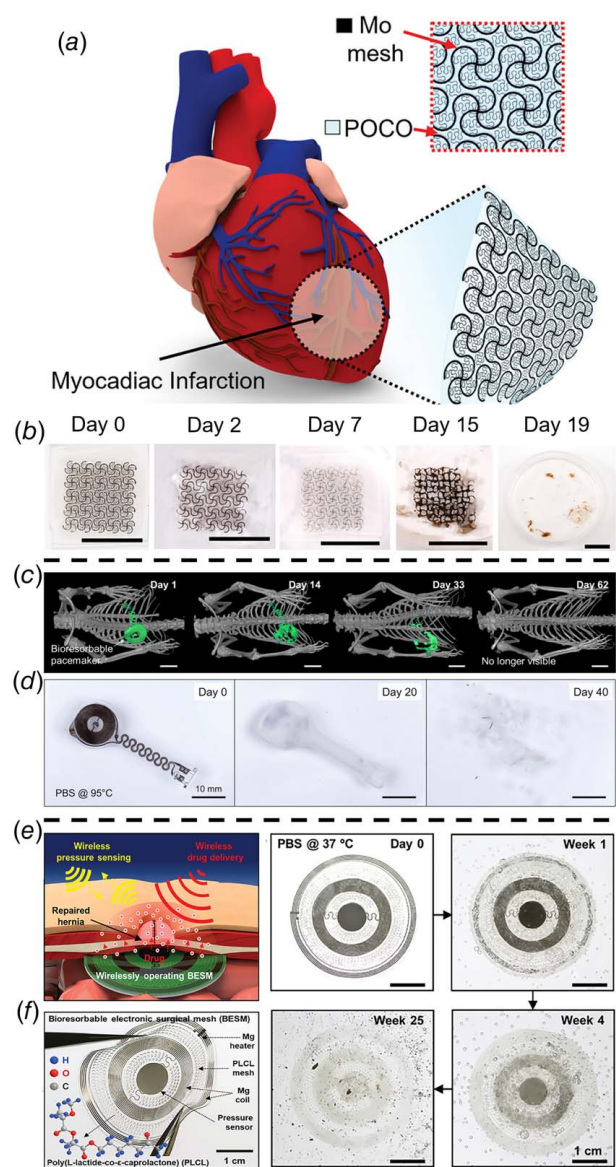


Fig. 2 Bioresorbable electronics for cardiac and drug delivery applications. (a) Illustration of resorbable serpentine mesh in the epicardial surface. **(b)** Optical images of the dissolution kinetics of the serpentine mesh in Dulbecco Phosphate Buffered Saline (DPBS) (pH = 7.4) at 75 °C, scale bar is 1 cm. (Reproduced from Ryu et al. [10] with permission from John Wiley and Sons.) **(c)** Computed tomography images of rats with bioresorbable electronic device over 9 weeks, scale bar is 10 mm. **(d)** Photographs of bioresorbable device over 40 days in PBS (pH = 7.4) at 95 °C, scale bar is 10 mm. (Reproduced from Choi et al. [11] with permission from American Association for the Advancement of Science.) **(e)** Illustration of wireless postoperative sensor showing the sensing and drug delivery mechanisms. **(f)** Optical image of flexible wireless sensor showcasing all the functional elements and undergoing resorption over 25 weeks in PBS (pH = 7.4) at 37 °C, scale bar is 1 cm. (Reproduced from Kaveti et al. [12] with permission from John Wiley and Sons.)

ranging from days to weeks. This implies that as the patient heals and recovers, the materials and mechanisms that ensure conformal adhesion and contact between the implant and biological tissues while providing sensing or therapeutic functionality, undergo continuous chemical or physical changes. Readers are referred to recent reviews for detailed discussion on the history [40], materials [9,39], models [41], medical devices [42], and ongoing efforts toward clinical translation and postoperative care [37,38].

How Are Material Properties Changing? What Governs Such Change?

As alluded to in Fig. 1, the mechanisms that govern material and structural changes in bioresorbable electronics involve a complex interplay of physical and chemical reactions. Specifically, in porous materials, water molecule diffusion, and crystalline structures, surface reactions govern the transient response. Over time, these mechanisms modify the device's initial geometry and functional response, as demonstrated by the transient disintegration of essential components captured in the optical images in Fig. 2. Experimentally, transiency is observed through changes in electrical properties, such as resistance in dissolving thin metallic films. The J-shaped curves representing the nonlinear, exponentially increasing resistance (caused by the rapid reduction in film thickness) are highly sensitive to factors such as thickness, temperature, and pH, which is consistent with observations from bulk erosion [43,44]. Multimaterial strategies, like the incorporation of a polymeric passivation (or encapsulation) layer or coatings, can be used to tailor the degradation of the overall system and delay the rapid degradation of the metallic or structural layers. Scanning electron microscope images of a micro-resonator submerged in phosphate-buffered saline (PBS, pH 7.4) at 37 °C reveal microstructural crack propagation caused by hydrolysis, resulting in a nonuniform surface that ultimately leads to mechanical and electrical device failure [45]. Additional metrics that characterize structural losses due to water permeability include the weight loss or water up-taken percentage, especially for hydrophobic polymeric barriers extending the lifetime of the bioelectronic device [46]. Similar material degradation kinetics are observed in eco- and bioresorbable systems, where fabrication techniques such as sewing [47] or electrospinning [48] enable custom patterning and the creation of highly stretchable, mechanically conformal degradable systems designed for cyclic operation. Continuous water absorption in these systems leads to the disassembly of structural threads, progressively reducing flexural and bending stiffness over time and ultimately rendering the devices unusable.

How Important Is the Surrounding Environment?

The diverse applications for bioresorbable electronics are driven, in part, by their ability to maintain reliable and stable operation across variable physiological (for implants) and environmental (for eco-resorbable systems) conditions. These conditions play a critical role in defining the degradation timeline and outcome of high-performance transient electronics. Factors such as pH, temperature, humidity, and ionic content significantly influence key chemical reactions, including hydrolysis—a common process driving the rate of dissolution of transient devices in biofluids and other solutions. Seminal experimental studies on electronic materials and components demonstrate that the dissolution rates of monocrystalline silicon nanomembranes [3], which are important in high-performance semiconductor devices, and silicon oxides and nitrides [49], acting as dielectric or encapsulation layers, are strongly dependent on the ionic content, pH level, and temperature (room or physiological) of the surrounding aqueous solutions [25]. The experiments reveal that dissolution rates increase with rising temperatures, scaling in the form of an Arrhenius trend, and showed a strong, linear dependence on pH levels when plotted on a logarithmic scale. To ensure prolonged mechanical and electrical stability, slow and controlled dissolution of electronic components in bioresorbable interfaces is essential for enabling transient systems capable of recording, stimulating, or sensing health-related parameters.

As previously discussed, temperature gradients and pH levels are critical environmental factors influencing the dissolution and degradation rates of biodegradable materials, particularly in transient measurement platforms for biofluid detection and sensing. However, the overall impact of these factors ultimately depends

on the physics couplings between the dissolution of the material constituents, resorption kinetics, and efficacy of the mechanical and material strategies to encapsulate and protect the internal device components. Certain implantable applications, such as biodegradable arterial scaffolds, may exhibit preferential degradation mechanisms where byproducts are not immediately cleared but instead accumulate around the degradable stent, catalyzing additional degradation processes that promote bulk erosion. Computational models, considering flow and transport phenomena, predict degradation kinetics, monitor byproduct accumulation in the surrounding environment, and quantify the sensitivity of the polymer structure to these processes [50]. Currently, the ease in tunability of a device's lifetime depends on the composition of the surrounding environment, with strategies to protect, extend, and control degradation primarily driven by integration with various classes of bioresorbable or biodegradable materials. Thus, controlled transiency relies on strategic multimaterial layouts that respond to the surrounding environment. Examples include using natural waxes as hydrophobic barriers to intentionally delay degradation [51], achieving moisture-triggered hydrolysis with polyanhydride substrates for precise degradation control [52], and incorporating sucrose and gelatin fillers into a polymer matrix to regulate transiency and mechanical properties [53]. In a similar vein, spatiotemporal deformations in the tissue environment subject implantable bioresorbable electronics to strain gradients that, if excessive, can limit the flexibility of the device to respond mechanically without fracturing [41,54,55] and damage other components that alter the stability and intended degradation timescales.

Partial or Complete Degradation? What Stops Working First?

Early approaches to develop biodegradable technologies focused on organic substrates in microelectromechanical systems, achieving near-complete degradation [56,57]. The rapid progress from simple, partially resorbable passive systems to high-performance biodegradable semiconductor devices with complete bioresorbable capabilities has significantly expanded research opportunities, enabling the exploration of transient behaviors and physiological interactions that were previously underexplored, or in some cases, impossible to realize with *everlasting* and rigid technologies. To date, the availability of bioresorbable materials for conductors, semiconductors, and insulators has enabled the complete degradation of components, including transistors, diodes, sensors, and power sources for sophisticated integrated circuits that vanish over controlled timescales [9].

As alluded to in the previous responses, evolving material properties and the relevance of the surrounding environment cannot be underscored. The lifetime of these bioresorbable electronic devices can be divided into two distinct timescales: the partial (or functional) timescale and the complete resorption timescale. Consider the stretchable cardiac mesh patch [10] shown in Fig. 2(a), where fractal mechanics enhances surface area coverage while preserving stretchability. Temporal dissolution images in Fig. 2(b) reveal that the secondary serpentine traces degrade within 2 days, while the primary serpentine traces remain for up to 19 days. Now, as an example of multicomponent systems, the flexible bioresorbable pacemaker [11] is shown in Figs. 2(c) and 2(d), where computed tomography images reveal complete resorption of the device in a rat over 9 weeks, while its functional lifetime is approximately 1 week. Optical images in accelerated in vitro conditions reveal the sequential resorption process, with the energy-harvesting coil and electrodes degrading first (after 20 days), followed by the polymer encapsulation layer (after 40 days). A similar representative example, shown in Figs. 2(e) and 2(f), features wireless surgical mesh for pressure sensing and drug delivery [12]. At body temperature, these implants have a functional lifetime of approximately 1 week, while complete resorption may take up to 25 weeks. Overall, the impact of transient mechanics on reshaping geometry and influencing material resorption timescales remains an

open topic of discussion, particularly for emerging devices where the efficiency of multiple degradable subsystems depends on prolonged stability.

What Is the Connection Between Transient Mechanics and Biomedicine?

One of the most compelling applications of bioresorbable electronics is the development of multifunctional implants capable of adapting both mechanically and electrically to the surrounding physiological environment. The central concept, inspired by biological systems, is based on the interactions and mechanisms that cells and tissues influence and are influenced by their surrounding environments—specifically, for the envisioned systems, the transient mechanical environment (e.g., forces and deformations), to sense or function. Arguably, the most significant advantage of bioresorbable devices is complete dissolution without causing harm to the biological environment, a condition primarily driven by a strategic selection of biocompatible materials [37]. Then, as long as the materials reabsorb over the projected lifetime, the changing structural response (across length scales) can be leveraged for mechanics manipulation, sensing, or wrapping. For example, consider a thin bioresorbable film with bending stiffness EI , thickness h , width b , and length $2L$, wrapped on a cylinder with radius R . The dissolution kinetics will govern the rate of change in the film's geometric and mechanical properties, as referenced in Fig. 1(b) and illustrated by the devices in Fig. 2, changing, among other things, the adhesion energy γ between the surface and the film. Mechanics analysis reveals the underlying physics to wrap (partially or completely) the functional thin films into complex surfaces [58] where dissolvable bio-interfaces ensure conformal wrapping, which is a critical mechanics requirement for neural interfaces [23,24,26]. Another intriguing connection lies in the complex interplay between mechanical forces and the surrounding soft tissue. It is well established that physical stimuli, such as tensile, contractile, and shear forces, trigger cellular responses that can collectively contribute to performing specific functions [59]. Mechanics design of thin bioresorbable films, guided by topology optimization for optimal material distribution, can be used to locate strain gradients within bioresorbable electronic devices. Those gradients not only enable mechanical programmability in devices to disintegrate with the surrounding tissue but also allow for the regulation of the forces experienced by surrounding cells as the device gradually reabsorbs into the body. A similar strategy is used in structural degradable orthopedic implants, where biomechanical loads are gradually transferred to the bone during healing. Clinical studies showed that as the implant's microstructure degrades—over much longer timescales, typically several months to significantly reduce the structural relevance and up to a year for complete resorption—it simultaneously promotes the growth of new bone [60]. Precise control of transient mechanical behavior—ranging from hours or days for ultra-thin bioresorbable electronics to months or years for structural implants—can offer valuable insights into the effects of imposing mechanical constraints on both soft and hard tissues.

How Can Models Predict Resorption, Degradation, and Disintegration?

The dissolution process of bioresorbable electronics involves complex degradation kinetics that are highly dependent on the material composition, form factor, and surrounding environment. Analytical models for single-layer and double-layer reactive diffusion in porous and crystalline materials have been widely adopted [8] to predict the lifetime of several bioelectronic devices. Their strong alignment with experimental results has clarified the governing mechanisms driving resorption in these types of thin bioresorbable electronic devices (Fig. 3). Recent studies have extended the initial theory to incorporate thicker encapsulations

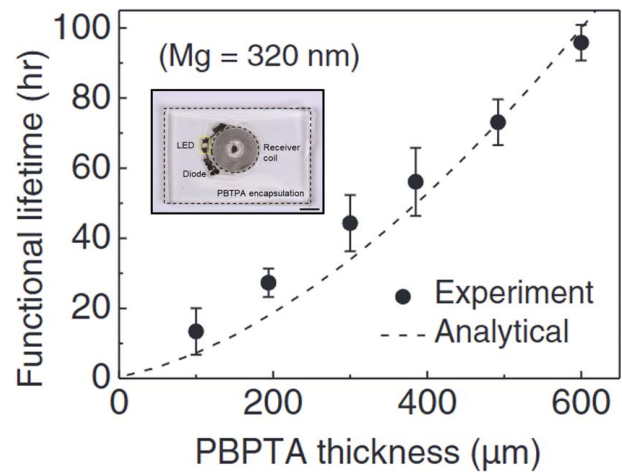


Fig. 3 Prediction of functional lifetimes. Functional lifetime, defined as the time where the resistance remains finite, of magnesium electrodes with variable polymeric encapsulation. (Reproduced from Choi et al. [46] with permission from John Wiley and Sons.)

[61], which are preferred for prolonging the functional lifetime of such devices.

For one-dimensional reactive diffusion, the mass conservation equations are

$$D_f \frac{\partial^2 w}{\partial z^2} - k_f w - \frac{\partial w}{\partial t} = 0 \quad 0 < z < h_f \quad (1)$$

$$D_{en} \frac{\partial^2 w}{\partial z^2} - k_{en} w - \frac{\partial w}{\partial t} = 0 \quad h_0 < z < h_f + h_{en} \quad (2)$$

where w represents the concentration of water, which varies with position z and time t . The initial thickness of the functional layer and the encapsulation layer are h_f and h_{en} , respectively. The properties D_f and D_{en} are the diffusivities, while k_f and k_{en} are hydrolysis reaction constants, both of which depend on the material composition. The solution to Eqs. (1) and (2) takes the form $w(z, t) = w_s(z) + w_h(z, t)$, where w_s represents the steady-state part and w_h is the transient part. Numerical methods, such as finite element analysis, can be used to model two- or three-dimensional systems where applying boundary conditions is more complex and edge effects influence the concentration profiles. Similar reactive-diffusion computational frameworks have been used in the past to model the degradation of metals and characterize transient topology using the level-set method [62]. Apart from water concentration, a theory for transient mechanics characteristics and other multiphysics couplings is missing. In particular, we note that *computationally* the degradation profiles neglect the influence of microcracks and chemo-mechanical characteristics of the resorbable systems. However, some transport models, using adaptive meshing techniques, have implemented schemes to solve the surface phase-change problem with moving boundaries to predict mass loss in 3D stent geometries [63].

Degradation mechanisms are nontrivial to implement, and biological environments introduce a high variability making the modeling particularly challenging. One numerical approach is to introduce a damage field variable D of the form

$$D = D_U + D_{SC} \quad (3)$$

$$\dot{D}_U = \frac{\delta_U}{L_e} k_U \quad (4)$$

where D_U represents uniform corrosion and D_{SC} represents a stress-dependent localization term where the damage evolution term $\dot{D}_U$

is proportional to the ratio between the mesh-independent characteristic dimension δ_U of the corrosion process, the characteristic length of the elements L_e , and a kinetics term k_U . This damage approach has been used to model corrosion in biodegradable stents [64–66].

How Can Transient Mechanics Properties Be Used to Design Multifunctional Devices?

Perhaps an underexplored direction in bioresorbable electronics is the concept of actively controlling mechanical properties over time within a singular functional timescale. This approach envisions a “transient mechanics” response that is not merely a byproduct of dissolution but intentionally programmed to align with it. The idea of transient mechanics responses is motivated, in some ways, from structural constraints to insert, position, and manipulate devices. Engineering transient material characteristics to program the strength, stiffness, and compressibility of future bioresorbable electronics can provide future directions to decouple complex body signals, enable preferential degradation patterns, and regulate tissue-device interfaces. Figure 4 quantifies the strain levels experienced by a representative bioresorbable device undergoing complex mechanical deformations, such as twisting and bending (Fig. 4(a)). Simulation results in Fig. 4(b) define the initial elastic limits of the functional electronic layer, ensuring that the device is protected against material yielding and fracture when in operation. During resorption, these elastic limits decrease at a rate proportional to the diffusion and reaction kinetics of the resorption process. Initial mechanical properties—such as high strength for load-bearing implants, high stretchability for dynamic tissue motion, or high conformability for curvilinear integration—adapt progressively to the surrounding environment. Examples include degradable microneedles designed to generate sufficient penetration force to puncture the skin layers [33] and deliver combined electrical and drug stimulation to promote muscle healing while minimizing inflammation. Recently, the growing interest in flexible neurostimulation technologies for wound healing and pain management [19,22] promotes multifunctional designs, with electrical and fluidic subsystems, that are mechanically compliant and wrap around nerves. Some might argue that, from a mechanical perspective, devices with ultra-thin form factors already offer exceptional compliance for integration with various types of biological tissue. However, as discussed earlier, the mechanical transiency goes beyond the device and into the environment to provide a unique

opportunity to understand how surrounding tissue—whether nerves, muscles, the epicardial surface, or the brain—responds to and evolves with multifunctional stimulation. More interestingly, deploying pairs or networks of multifunctional bioresorbable devices, such as a transient body sensor network, can provide spatial information about mechanical changes in the tissue opening vast possibilities for advanced sensing capabilities and translational applications.

Where Is the Energy Coming From? Batteries or Wireless?

One of the fundamental challenges in bioresorbable electronics, and bio-integrated electronics more broadly, is the development of power supply sources, such as batteries [67,68] and supercapacitors [69] to eliminate the need for wired energy sources. These power sources must maintain the compact, miniaturized, and practical design of the overall implantable integrated system while providing stable and useful energy density to circuit components throughout their functional lifetime. As the complexity of bioresorbable electronic circuits increases, along with the number of active and passive components, the energy demand and device footprint grow accordingly to sustain functionality. This energy requirement is crucial for monitoring transient or dynamic biological events, some of which require highly conformal mechanics for biodegradable and stretchable batteries [70,71] or mechanical energy harvesters based on triboelectric and piezoelectric effects [72].

An alternative to stretchable batteries is wireless power transfer technologies, particularly those that enable simultaneous data and power transmission through magnetic loop antennas for near-field communication (NFC) radio frequency (13.56 MHz), achieved via inductive coupling. Examples include compact, planar, bioresorbable coils with substrates and encapsulations that aim to enhance the magnetic field surrounding the coil (Fig. 5(a)), delay the diffusion of water molecules using wax substrates (Figs. 5(b) and 5(c)) and edible oils (Fig. 5(d)) as encapsulations. The wireless systems in Fig. 5 establish a connection between an external, skin-mounted transmitter coil and an implantable bioresorbable coil. The efficiency of power transmission depends on the frequency, self-inductance, and mutual inductance of the coils, and is highly sensitive to the orientation and distance between them [73]. Wireless power transfer strategies promote the miniaturization of bioresorbable electronics, enabling fully or partially implantable integrated systems. For example, bioresorbable pacemakers [11,13,47] featuring double-layer energy-harvesting coils and stretchable stimulation electrodes entirely implanted within the body. In contrast, bioresorbable electrotherapy systems for chronic wounds [74] are partially implantable, with only the stretchable electrodes in contact with the wound surface. Depending on the clinical application, wireless design and alternative energy sources become important when the following situations occur:

- (1) The distance between the coils is unusually large: Since the magnetic field strength decreases with the cube of the distance between the coils ($B \propto r^{-3}$), the power transfer efficiency is highly sensitive to coil separation. This limitation is particularly relevant for deep tissue sensing and monitoring, where alternative strategies, such as ultrasound, are often preferred [75]. In some cases, incorporating a magnetic field concentrator (Fig. 5(a)) layer made from biodegradable iron oxide (Fe_2O_3) nanoparticles can enhance the output voltage and current in the receiver [16]. However, the working distance remains limited to approximately the largest characteristic length of the coils.
- (2) The deformation of the device is large: The metallic traces (e.g., Mg, Mo, Zn, Fe, W) [43], and in some cases, room-temperature liquid metals such as EGaIn or GaInSn [76], used in the antennas and electrode interconnects of bioresorbable devices must deform elastically to prevent material

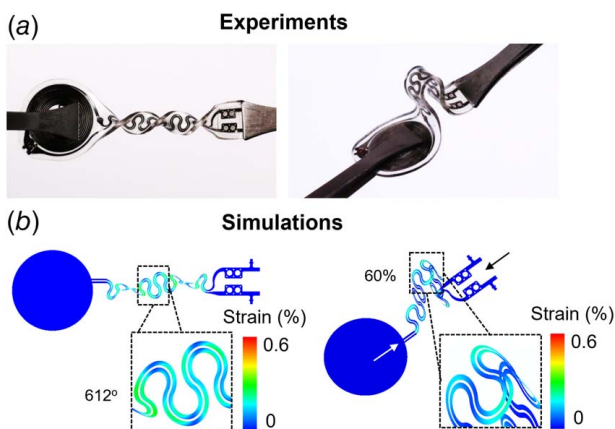


Fig. 4 Mechanics modeling of bioresorbable electronics. (a) Photographs of bioresorbable pacemakers with energy-harvesting coil and serpentine interconnects during twisting and bending deformations. (b) Corresponding finite element results of the strain contours in the metal layer indicating that the material does not yield. (Reproduced from Choi et al. [11] with permission from the American Association for the Advancement of Science.)

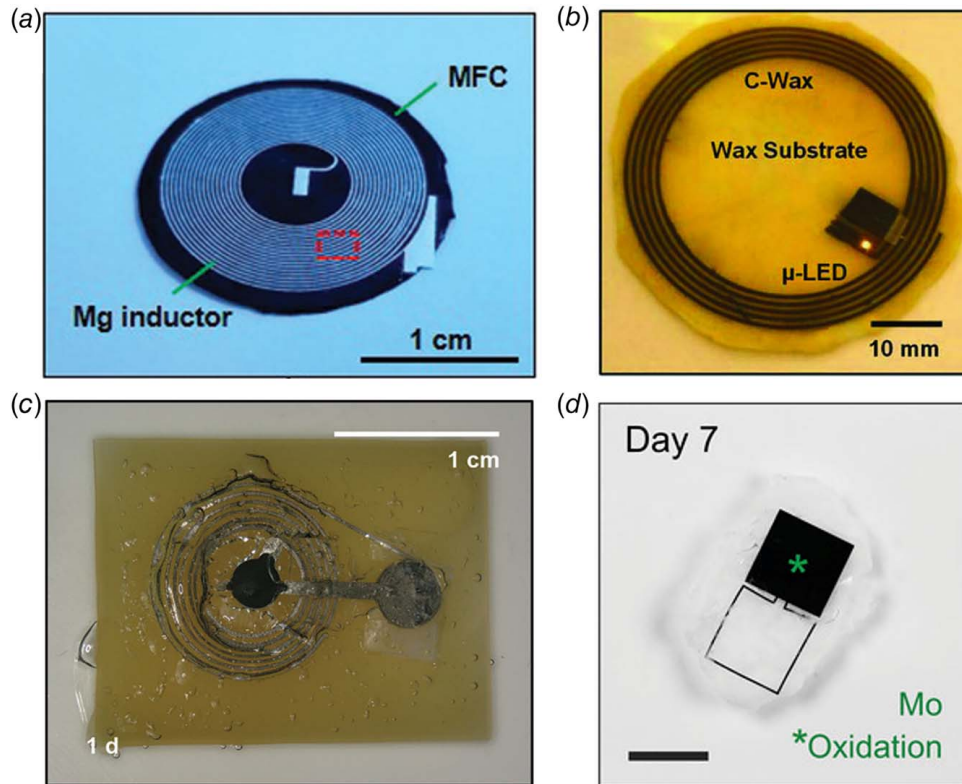


Fig. 5 Encapsulations in bioresorbable electronics. (a) Optical image of bioresorbable magnesium coil with a magnetic flux concentration, scale bar 1 cm. (Reproduced from Guo et al. [16] with permission from John Wiley and Sons.) **(b)** Optical images of radiofrequency coil using C-wax substrate to enable wireless sensing, scale bar is 10 mm. (Reproduced from Won et al. [51] with permission from John Wiley and Sons.) **(c)** Degradation process of temperature sensors after 1 day showing the internal structure of the device under PBS (pH = 7.4) at 37 °C, scale bar 1 cm. (Reproduced from Lu et al. [18] with permission from John Wiley and Sons.) **(d)** Photographs of an inductive-capacitive system after 7 days in PBS (pH = 7.4) at 75 °C, scale bar 10 mm. (Reproduced from Lee et al. [17] with permission from John Wiley and Sons.)

fractures. Ultra-thin serpentine mesh structures are widely used in bio-integrated electronics for their nonlinear mechanics, which enable them to accommodate large mechanical deformations. Combining serpentine arrays with stretchable mesh electrodes [77], designed to match the modulus of biological tissues, enables conformal lamination onto time-dynamic, curvilinear surfaces and tissues, allowing for the extraction of relevant health metrics. However, large deformations alter the electromagnetic couplings, specifically the inductive behavior of the coils and resonant frequency, affecting the stability of data and power transmission. To address this, mechanics scaling laws have been proposed that optimize the macro- and micro-geometrical parameters of planar multiturn serpentine coil architectures, reducing sensitivity to uniaxial and biaxial deformations [78].

- (3) The dielectric changes in the surrounding environment: Encapsulating polymers or surrounding tissues with high dielectric constants can lower the resonant frequency of antenna coils, thereby affecting power transfer efficiency and electromagnetic couplings. As water molecules (or other biofluids) diffuse through the encapsulation and react with the electrodes, the effective permittivity of the encapsulation increases, causing a shift in the resonance of the energy-harvesting circuit. Recent experiments have slowed this diffusion process by introducing a water barrier, such as edible oil (Fig. 5(d)), which stabilizes the resonant frequency of the inductive coils for up to 30 days [17]. Other studies have developed a library of copolymers that function as water barriers, extending implantable device functionality

by several weeks [79]. Readers can refer to a topical review [80] that discusses the dielectric properties of tissues of interest for bioresorbable electronics, including skin, adipose tissue, brain tissue, and breast tissue, among others. Additionally, a comprehensive materials review [39] provides an overview of bioresorbable polymers used as encapsulation materials, such as poly(lactic-co-glycolic) acid and polyanhydrides.

Energy management, in particular, is important in biodegradable electronics, as excessive energy can cause unsafe local tissue heating (1 °C or more) or exceed specific absorption rate (SAR) limits (above 1.6 W/kg averaged over 1 g of tissue). Careful engineering designs can help mitigate electromagnetic losses caused by the surrounding environment while adhering to safety regulations for SAR and biological heating caused by the induced currents. Numerical simulations suggest that body-integrated devices, modeled with implantable radio frequency coils in canine and rat models, can effectively dissipate heat during duty cycle operation. Maximum tissue temperature changes were limited to 0.035 °C, with SAR values remaining below 0.075 W/kg [11]. In contrast, experiments in air and water using wireless microresonators as heaters demonstrate the potential for localized drug delivery and thermal therapies by selectively melting nearby bioresorbable elements [45]. Mild thermal actuation, however, can be employed to alter the diffusivity of thermo-responsive encapsulating materials, while controlling tissue inflammation and accelerating drug release into the body, as demonstrated in the treatment of abdominal hernias [12]. However, caution must be taken with thermally

actuated bioresorbable implants, as excessive temperatures can compromise the mechanical and chemical functionality of other components within the implant.

What Are Some Open Areas of Transient Mechanics Research in Bioresorbable Electronics?

The development of translational devices with fully bioresorbable capabilities has been largely driven by active efforts from the materials science, chemistry, and mechanics communities. Since these devices are designed to be resorbed by the body, the focus has been on developing tools and materials with controllable resorption capabilities, tailored to work on finite lifetimes while matching or exceeding the performance of their permanent counterparts. Research directions on the mechanics of bioresorbable electronics have, in part, focused on: (1) optimizing electronic circuit and mesh layouts to prevent material failure under cyclic deformations such as stretching, twisting, bending, poking, and folding; (2) miniaturizing device form factors to maximize compliance through enhanced flexibility and stretchability on time-dynamic surface to facilitate pressure and strain sensing modalities while reducing interfacial stresses; and (3) optimizing planar and three-dimensional mesostructures in microsystems technologies to achieve zero-waste, environmentally friendly, electronics [81,82]. Here, we highlight a few topics and research directions related to *transient mechanics* that may be of interest to the mechanics community.

Perhaps one of the biggest needs is the development of computational models capable of predicting the dissolution profiles of complete multimaterial bioresorbable systems, including the influence of boundary effects on the overall resorption kinetics. Experimental testing, typically conducted in water or saline solutions with devices fully submerged at room or elevated temperatures, has generally outpaced modeling efforts. This is because experimental testing, supported by imaging at various time points, provides a comprehensive dissolution history revealing that certain regions of the device dissolve and fracture earlier than others. From a computational perspective, extending models from one-dimensional to three-dimensional is nontrivial because the multiphysics coupling (chemo-mechanical) and the associated boundary conditions are not fully understood, particularly when transient damage or failure criteria dictate how the device fractures into smaller pieces. Currently, the mechanics (i.e., modulus, stiffness, stretchability) of bioresorbable devices are established before resorption. Understanding how the bioresorbable device's mechanics evolve locally during diffusion and hydrolysis reactions is particularly valuable, especially for wound healing applications, where mechanical forces on cells play a critical role. Mechanically tunable bioresorbable implants offer a means to control the force field and strain gradients locally, both spatially and temporally. A similar approach can be used to design next-generation drug delivery devices and surgical meshes, where local control of transient mechanics within the resorbable platform enables programmable delivery in reservoirs and regions specifically designed to initiate fracture.

An exciting future direction in implantable wireless body area networks is the in vivo characterization of soft tissue mechanical properties over time. This approach, which relies on electromagnetic and mechanical couplings between the scattering S (S parameters) and the deformation gradient $\mathbf{F}$ tensors in radio frequency circuits, could provide valuable insights into physiological responses, kinematics, and the evolution of mechanical and electrical properties of biological tissues to replicate them in other engineering systems like soft sensors and actuators for digital health applications. Their mechanical advantage to conformally match extreme curvatures and wrap around nerves, muscles, and other curvilinear surfaces, could, in principle, provide valuable information about the time-dynamic mechanisms that incentivize tissue growth and remodeling. These principles naturally extend to previously unexplored systems, such as bone, enabling the development of osseo-surface electronics [83] and orthopedic implants [32]. As

discussed in previous sections, novel forms of transient mechanics appeal not only for their technological potential but also for their impact on the surrounding biological environment. These new classes of devices can facilitate multimodal sensing, provide transient structural and fixation support for musculoskeletal loads, and integrate seamlessly with newly formed bone microstructures.

Finally, three-dimensional architected electronics, created through mechanically guided 3D assembly of planar structures [84], have shown significant potential in applications such as microelectronics, robotics, and healthcare. Exploring the connection between inverse design methods, biodegradable materials, and transient mechanical responses offers exciting opportunities to manufacture flexible, multiscale, eco-resorbable structures [47,81] and arrays capable of performing complex sensing and modulation tasks before disintegrating.

Acknowledgment

Raudel Avila gratefully acknowledges support from seed grants by the Educational and Research Initiatives for Collaborative Health (ENRICH) Office at Rice University and the Rice University Space Institute. Nicole Carusetta gratefully acknowledges support from the Medical Humanities Research Institute at Rice University.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

No data, models, or code were generated or used for this article.

References

- [1] Perkins, D. N., Brune Drisse, M. N., Nxele, T., and Sly, P. D., 2014, "E-Waste: A Global Hazard," *Ann. Glob. Health*, **80**(4), pp. 286–295.
- [2] Mir, S., and Dhawan, N., 2022, "A Comprehensive Review on the Recycling of Discarded Printed Circuit Boards for Resource Recovery," *Resour. Conserv. Recycl.*, **178**, p. 106027.
- [3] Hwang, S.-W., Tao, H., Kim, D.-H., Cheng, H., Song, J.-K., Rill, E., Brenckle, M. A., et al., 2012, "A Physically Transient Form of Silicon Electronics," *Science* (1979), **337**(6102), pp. 1640–1644.
- [4] Hwang, S. W., Song, J. K., Huang, X., Cheng, H., Kang, S. K., Kim, B. H., Kim, J. H., Yu, S., Huang, Y., and Rogers, J. A., 2014, "High-Performance Biodegradable/Transient Electronics on Biodegradable Polymers," *Adv. Mater.*, **26**(23), pp. 3905–3911.
- [5] Han, W. B., Lee, J. H., Shin, J. W., and Hwang, S. W., 2020, "Advanced Materials and Systems for Biodegradable, Transient Electronics," *Adv. Mater.*, **32**(51), pp. 1–17.
- [6] Hwang, S. W., Kim, D. H., Tao, H., Kim, T. I., Kim, S., Yu, K. J., Panilaitis, B., et al., 2013, "Materials and Fabrication Processes for Transient and Bioresorbable High-Performance Electronics," *Adv. Funct. Mater.*, **23**(33), pp. 4087–4093.
- [7] Ko, G. J., Kang, H., Han, W. B., Dutta, A., Shin, J. W., Jang, T. M., Han, S., et al., 2024, "Materials and Designs for Extremely Efficient Encapsulation of Soft, Biodegradable Electronics," *Adv. Funct. Mater.*, **34**(39), p. 2403427.
- [8] Li, R., Cheng, H., Su, Y., Hwang, S. W., Yin, L., Tao, H., Brenckle, M. A., et al., 2013, "An Analytical Model of Reactive Diffusion for Transient Electronics," *Adv. Funct. Mater.*, **23**(24), pp. 3106–3114.
- [9] Zhang, Y., Lee, G., Li, S., Hu, Z., Zhao, K., and Rogers, J. A., 2023, "Advances in Bioresorbable Materials and Electronics," *Chem. Rev.*, **123**(19), pp. 11722–11773.
- [10] Ryu, H., Wang, X., Xie, Z., Kim, J., Liu, Y., Bai, W., Song, Z., et al., 2023, "Materials and Design Approaches for a Fully Bioresorbable, Electrically Conductive and Mechanically Compliant Cardiac Patch Technology," *Adv. Sci.*, **10**(27), pp. 1–12.
- [11] Choi, Y. S., Jeong, H., Yin, R. T., Avila, R., Pfenniger, A., Yoo, J., Lee, J. Y., et al., 2022, "A Transient, Closed-Loop Network of Wireless, Body-Integrated Devices for Autonomous Electrotherapy," *Science* (1979), **376**(6596), pp. 1006–1012.
- [12] Kaveti, R., Lee, J. H., Youn, J. K., Jang, T. M., Han, W. B., Yang, S. M., Shin, J. W., et al., 2024, "Soft, Long-Lived, Bioresorbable Electronic Surgical Mesh With Wireless Pressure Monitor and On-Demand Drug Delivery," *Adv. Mater.*, **36**(11), pp. 1–11.
- [13] Choi, Y. S., Yin, R. T., Pfenniger, A., Koo, J., Avila, R., Benjamin Lee, K., Chen, S. W., et al., 2021, "Fully Implantable and Bioresorbable Cardiac Pacemakers Without Leads or Batteries," *Nat. Biotechnol.*, **39**(10), pp. 1228–1238.

- [14] Li, S., Lu, D., Li, S., Liu, J., Xu, Y., Yan, Y., Rodriguez, J. Z., et al., 2024, "Bioresorbable, Wireless, Passive Sensors for Continuous pH Measurements and Early Detection of Gastric Leakage," *Sci. Adv.*, **10**(16), pp. 16–22.
- [15] Hwang, S. W., Huang, X., Seo, J. H., Song, J. K., Kim, S., Hage-Ali, S., Chung, H. J., et al., 2013, "Materials for Bioresorbable Radio Frequency Electronics," *Adv. Mater.*, **25**(26), pp. 3526–3531.
- [16] Guo, Q., Koo, J., Xie, Z., Avila, R., Yu, X., Ning, X., Zhang, H., et al., 2019, "A Bioresorbable Magnetically Coupled System for Low-Frequency Wireless Power Transfer," *Adv. Funct. Mater.*, **29**(46), pp. 1–8.
- [17] Lee, G., Does, M. D., Avila, R., Kang, J., Harkins, K. D., Wu, Y., Banks, W. E., et al., 2024, "Implantable, Bioresorbable Radio Frequency Resonant Circuits for Magnetic Resonance Imaging," *Adv. Sci.*, **11**(27), pp. 1–11.
- [18] Lu, D., Yan, Y., Avila, R., Kandela, I., Stepien, I., Seo, M. H., Bai, W., et al., 2020, "Bioresorbable, Wireless, Passive Sensors as Temporary Implants for Monitoring Regional Body Temperature," *Adv. Healthcare Mater.*, **9**(16), pp. 1–11.
- [19] Lee, D. M., Kang, M., Hyun, I., Park, B. J., Kim, H. J., Nam, S. H., Yoon, H. J., et al., 2023, "An On-Demand Bioresorbable Neurostimulator," *Nat. Commun.*, **14**(1), pp. 1–11.
- [20] Choi, Y. S., Hsueh, Y. Y., Koo, J., Yang, Q., Avila, R., Hu, B., Xie, Z., et al., 2020, "Stretchable, Dynamic Covalent Polymers for Soft, Long-Lived Bioresorbable Electronic Stimulators Designed to Facilitate Neuromuscular Regeneration," *Nat. Commun.*, **11**(1), pp. 1–14.
- [21] Lim, J. H., Han, W. B., Jang, T. M., Ko, G. J., Shin, J. W., Han, S., Kang, H., et al., 2024, "Synthesis of Shape-Programmable Elastomer for a Bioresorbable, Wireless Nerve Stimulator," *Biosens. Bioelectron.*, **254**, p. 116222.
- [22] Reeder, J. T., Xie, Z., Yang, Q., Seo, M. H., Yan, Y., Deng, Y., Jinkins, K. R., et al., 2022, "Soft, Bioresorbable Coolers for Reversible Conduction Block of Peripheral Nerves," *Science* (1979), **377**(6601), pp. 109–115.
- [23] Bae, J. Y., Hwang, G. S., Kim, Y. S., Jeon, J., Chae, M., Kim, J. W., Lee, S., et al., 2024, "A Biodegradable and Self-Deployable Electronic Tent Electrode for Brain Cortex Interfacing," *Nat. Electron.*, **7**(9), pp. 815–828.
- [24] Cho, M., Han, J. K., Suh, J., Kim, J. J., Ryu, J. R., Min, I. S., Sang, M., et al., 2024, "Fully Bioresorbable Hybrid Opto-Electronic Neural Implant System for Simultaneous Electrophysiological Recording and Optogenetic Stimulation," *Nat. Commun.*, **15**(1), pp. 1–16.
- [25] Yu, K. J., Kuzum, D., Hwang, S. W., Kim, B. H., Juul, H., Kim, N. H., Won, S. M., et al., 2016, "Bioresorbable Silicon Electronics for Transient Spatiotemporal Mapping of Electrical Activity From the Cerebral Cortex," *Nat. Mater.*, **15**(7), pp. 782–791.
- [26] Kang, S. K., Murphy, R. K. J., Hwang, S. W., Lee, S. M., Harburg, D. V., Krueger, N. A., Shin, J., et al., 2016, "Bioresorbable Silicon Electronic Sensors for the Brain," *Nature*, **530**(7588), pp. 71–76.
- [27] Ouyang, H., Li, Z., Gu, M., Hu, Y., Xu, L., Jiang, D., Cheng, S., et al., 2021, "A Bioresorbable Dynamic Pressure Sensor for Cardiovascular Postoperative Care," *Adv. Mater.*, **33**(39), pp. 1–9.
- [28] Palmroth, A., Salpavaara, T., Vuoristo, P., Karjalainen, S., Käriäinen, T., Miettinen, S., Massera, J., Lekkala, J., and Kellomäki, M., 2020, "Materials and Orthopedic Applications for Bioresorbable Inductively Coupled Resonance Sensors," *ACS Appl. Mater. Interfaces*, **12**(28), pp. 31148–31161.
- [29] Shin, J., Yan, Y., Bai, W., Xue, Y., Gamble, P., Tian, L., Kandela, I., et al., 2019, "Bioresorbable Pressure Sensors Protected With Thermally Grown Silicon Dioxide for the Monitoring of Chronic Diseases and Healing Processes," *Nat. Biomed. Eng.*, **3**(1), pp. 37–46.
- [30] Li, Z., Li, C., and Deng, Y., 2023, "Bioresorbable Pressure Sensor and Its Applications in Abnormal Respiratory Event Identification," *ACS Appl. Electron. Mater.*, **5**(3), pp. 1761–1769.
- [31] Lee, J. H., Bae, J. Y., Kim, Y. N., Chae, M., Lee, W. J., Lee, J., Kim, I. D., et al., 2024, "A Fully Biodegradable and Ultra-Sensitive Crack-Based Strain Sensor for Biomechanical Signal Monitoring," *Adv. Funct. Mater.*, **34**(41), p. 2406035.
- [32] Boutry, C. M., Kaizawa, Y., Schroeder, B. C., Chortos, A., Legrand, A., Wang, Z., Chang, J., Fox, P., and Bao, Z., 2018, "Pressure Sensor for Orthopaedic Application," *Nat. Electron.*, **1**(May), pp. 314–321.
- [33] Huang, Y., Li, H., Hu, T., Li, J., Yiu, C. K., Zhou, J., Li, J., et al., 2022, "Implantable Electronic Medicine Enabled by Bioresorbable Microneedles for Wireless Electrotherapy and Drug Delivery," *Nano Lett.*, **22**(14), pp. 5944–5953.
- [34] Lee, J., Cho, H. R., Cha, G. D., Seo, H., Lee, S., Park, C. K., Kim, J. W., et al., 2019, "Flexible, Sticky, and Biodegradable Wireless Device for Drug Delivery to Brain Tumors," *Nat. Commun.*, **10**(1), pp. 1–9.
- [35] Zhang, Y., Liu, F., Zhang, Y., Wang, J., D'Andrea, D., Walters, J. B., Li, S., et al., 2023, "Self-Powered, Light-Controlled, Bioresorbable Platforms for Programmed Drug Delivery," *Proc. Natl. Acad. Sci.*, **120**(11), p. e2217734120.
- [36] Lee, C. H., Kim, H., Harburg, D. V., Park, G., Ma, Y., Pan, T., Kim, J. S., et al., 2015, "Biological Lipid Membranes for On-Demand, Wireless Drug Delivery From Thin, Bioresorbable Electronic Implants," *NPG Asia Mater.*, **7**(11), p. e227–e227.
- [37] Li, C., Guo, C., Fitzpatrick, V., Ibrahim, A., Zwierstra, M. J., Hanna, P., Lechtig, A., Nazarian, A., Lin, S. J., and Kaplan, D. L., 2020, "Design of Biodegradable, Implantable Devices Towards Clinical Translation," *Nat. Rev. Mater.*, **5**(1), pp. 61–81.
- [38] Mirzajani, H., Zolfaghari, P., Akbari Nakhjavani, S., Koca, B. Y., Khodapanahandeh, M., and Urey, H., 2024, "Transient Implantable Electronics for Postsurgery Preventive Medicine," *Adv. Funct. Mater.*, **35**(3), p. 2413324.
- [39] Hwangbo, J., Seo, H., Sim, G., Avila, R., Nair, M., Kim, B., and Choi, Y., 2024, "Bioresorbable Polymers for Electronic Medicine," *Cell Rep. Phys. Sci.*, **5**(8), p. 102099.
- [40] Cha, G. D., Kang, D., Lee, J., and Kim, D. H., 2019, "Bioresorbable Electronic Implants: History, Materials, Fabrication, Devices, and Clinical Applications," *Adv. Healthcare Mater.*, **8**(11), pp. 1–20.
- [41] Cheng, H., and Vepachedu, V., 2016, "Recent Development of Transient Electronics," *Theor. Appl. Mech. Lett.*, **6**(1), pp. 21–31.
- [42] Singh, R., Bathaei, M. J., Istif, E., and Bekler, L., 2020, "A Review of Bioresorbable Implantable Medical Devices: Materials, Fabrication, and Implementation," *Adv. Healthcare Mater.*, **9**(18), pp. 1–25.
- [43] Yin, L., Cheng, H., Mao, S., Haasch, R., Liu, Y., Xie, X., Hwang, S. W., et al., 2014, "Dissolvable Metals for Transient Electronics," *Adv. Funct. Mater.*, **24**(5), pp. 645–658.
- [44] Von Burkersroda, F., Schedl, L., and Göpferich, A., 2002, "Why Degradable Polymers Undergo Surface Erosion or Bulk Erosion," *Biomaterials*, **23**(21), pp. 4221–4231.
- [45] Rüegg, M., Blum, R., Boero, G., and Brugger, J., 2019, "Biodegradable Frequency-Selective Magnesium Radio-Frequency Microresonators for Transient Biomedical Implants," *Adv. Funct. Mater.*, **29**(39), p. 1903051.
- [46] Choi, Y. S., Koo, J., Lee, Y. J., Lee, G., Avila, R., Ying, H., Reeder, J., et al., 2020, "Biodegradable Polyanhydrides as Encapsulation Layers for Transient Electronics," *Adv. Funct. Mater.*, **30**(31), pp. 1–10.
- [47] Wu, Y., Rytkin, E., Bimrose, M., Li, S., Choi, Y. S., Lee, G., Wang, Y., et al., 2023, "A Sewing Approach to the Fabrication of Eco/Bioresorbable Electronics," *Small*, **19**(49), pp. 1–10.
- [48] Najafabadi, A. H., Tamayol, A., Annabi, N., Ochoa, M., Mostafalu, P., Akbari, M., Nikkha, M., et al., 2014, "Biodegradable Nanofibrous Polymeric Substrates for Generating Elastic and Flexible Electronics," *Adv. Mater.*, **26**(33), pp. 5823–5830.
- [49] Kang, S. K., Hwang, S. W., Cheng, H., Yu, S., Kim, B. H., Kim, J. H., Huang, Y., and Rogers, J. A., 2014, "Dissolution Behaviors and Applications of Silicon Oxides and Nitrides in Transient Electronics," *Adv. Funct. Mater.*, **24**(28), pp. 4427–4434.
- [50] Ferdous, J., Kolachalama, V. B., and Shazly, T., 2013, "Impact of Polymer Structure and Composition on Fully Resorbable Endovascular Scaffold Performance," *Acta Biomater.*, **9**(4), pp. 6052–6061.
- [51] Won, S. M., Koo, J., Crawford, K. E., Mickle, A. D., Xue, Y., Min, S., McIlvried, L. A., et al., 2018, "Natural Wax for Transient Electronics," *Adv. Funct. Mater.*, **28**(32), pp. 1–10.
- [52] Gao, Y., Zhang, Y., Wang, X., Sim, K., Liu, J., Chen, J., Feng, X., Xu, H., and Yu, C., 2017, "Moisture-Triggered Physically Transient Electronics," *Sci. Adv.*, **3**(9), pp. 1–8.
- [53] Acar, H., Çinar, S., Thunga, M., Kessler, M. R., Hashemi, N., and Montazami, R., 2014, "Study of Physically Transient Insulating Materials as a Potential Platform for Transient Electronics and Bioelectronics," *Adv. Funct. Mater.*, **24**(26), pp. 4135–4143.
- [54] Çinar, S., Jamshidi, R., Chen, Y., Hashemi, N., and Montazami, R., 2016, "Study of Mechanics of Physically Transient Electronics: A Step Toward Controlled Transiency," *J. Polym. Sci., Part B: Polym. Phys.*, **54**(4), pp. 517–524.
- [55] Jamshidi, R., Çinar, S., Chen, Y., Hashemi, N., and Montazami, R., 2015, "Transient Bioelectronics: Electronic Properties of Silver Microparticle-Based Circuits on Polymeric Substrates Subjected to Mechanical Load," *J. Polym. Sci., Part B: Polym. Phys.*, **53**(22), pp. 1603–1610.
- [56] Bettinger, C. J., and Bao, Z., 2010, "Organic Thin-Film Transistors Fabricated on Resorbable Biomaterial Substrates," *Adv. Mater.*, **22**(5), pp. 651–655.
- [57] Kim, D. H., Kim, Y. S., Amsden, J., Panilaitis, B., Kaplan, D. L., Omenetto, F. G., Zakin, M. R., and Rogers, J. A., 2009, "Silicon Electronics on Silk as a Path to Bioresorbable, Implantable Devices," *Appl. Phys. Lett.*, **95**(13), p. 133701.
- [58] Kim, D.-H., Viventi, J., Amsden, J. J., Xiao, J., Vigeland, L., Kim, Y.-S., Blanco, J. A., et al., 2010, "Dissolvable Films of Silk Fibroin for Ultrathin Conformal Bio-Integrated Electronics," *Nat. Mater.*, **9**(6), pp. 511–517.
- [59] Barnes, L. A., Marshall, C. D., Leavitt, T., Hu, M. S., Moore, A. L., Gonzalez, J. G., Longaker, M. T., and Gurtner, G. C., 2018, "Mechanical Forces in Cutaneous Wound Healing: Emerging Therapies to Minimize Scar Formation," *Adv. Wound Care*, **7**(2), pp. 47–56.
- [60] Lee, J. W., Han, H. S., Han, K. J., Park, J., Jeon, H., Ok, M. R., Seok, H. K., et al., 2016, "Long-Term Clinical Study and Multiscale Analysis of In Vivo Biodegradation Mechanism of Mg Alloy," *Proc. Natl. Acad. Sci.*, **113**(3), pp. 716–721.
- [61] Zhang, H., Zhang, K., Rogers, J. A., and Huang, Y., 2024, "An Analytical Model of Reactive Diffusion for Transient Electronics With Thick Encapsulation Layer," *Mech. Mater.*, **191**, p. 104954.
- [62] Bajger, P., Ashbourn, J. M. A., Manhas, V., Guyot, Y., Lietaert, K., and Geris, L., 2017, "Mathematical Modelling of the Degradation Behaviour of Biodegradable Metals," *Biochem. Model. Mechanobiol.*, **16**(1), pp. 227–238.
- [63] Grogan, J. A., Leen, S. B., and McHugh, P. E., 2014, "A Physical Corrosion Model for Bioabsorbable Metal Stents," *Acta Biomater.*, **10**(5), pp. 2313–2322.
- [64] Grogan, J. A., Leen, S. B., and McHugh, P. E., 2013, "Optimizing the Design of a Bioabsorbable Metal Stent Using Computer Simulation Methods," *Biomaterials*, **34**(33), pp. 8049–8060.
- [65] Gastaldi, D., Sassi, V., Petrini, L., Vedani, M., Trasatti, S., and Migliauacca, F., 2011, "Continuum Damage Model for Bioresorbable Magnesium Alloy Devices —Application to Coronary Stents," *J. Mech. Behav. Biomed. Mater.*, **4**(3), pp. 352–365.
- [66] Wu, W., Gastaldi, D., Yang, K., Tan, L., Petrini, L., and Migliauacca, F., 2011, "Finite Element Analyses for Design Evaluation of Biodegradable Magnesium Alloy Stents in Arterial Vessels," *Mater. Sci. Eng., B*, **176**(20), pp. 1733–1740.

- [67] Yin, L., Huang, X., Xu, H., Zhang, Y., Lam, J., Cheng, J., and Rogers, J. A., 2014, "Materials, Designs, and Operational Characteristics for Fully Biodegradable Primary Batteries," *Adv. Mater.*, **26**(23), pp. 3879–3884.
- [68] Ko, G. J., Jang, T. M., Shin, D., Kang, H., Yang, S. M., Han, S., Kaveti, R., et al., 2024, "Long-Lasting, Flexible and Fully Bioresorbable AZ31-Tungsten Batteries for Transient, Biodegradable Electronics," *J. Mater. Chem. A*, **12**(47), pp. 32712–32720.
- [69] Lee, G., Kang, S. K., Won, S. M., Gutruf, P., Jeong, Y. R., Koo, J., Lee, S. S., Rogers, J. A., and Ha, J. S., 2017, "Fully Biodegradable Microsupercapacitor for Power Storage in Transient Electronics," *Adv. Energy Mater.*, **7**(18), pp. 1–12.
- [70] Rahmanudin, A., Mohammadi, M., Isacson, P., Li, Y., Seufert, L., Kim, N., Mardi, S., Engquist, I., Crispin, R., and Tybrandt, K., 2024, "Stretchable and Biodegradable Plant-Based Redox-Diffusion Batteries," *Mater. Horiz.*, **11**(18), pp. 4400–4412.
- [71] Karami-Mosammam, M., Danninger, D., Schiller, D., and Kaltenbrunner, M., 2022, "Stretchable and Biodegradable Batteries With High Energy and Power Density," *Adv. Mater.*, **34**(32), pp. 1–11.
- [72] Dong, L., Shan, L., Wang, Y., and Liu, J., 2025, "Biodegradable Power Sources for Transient Bioelectronics," *Supramol. Mater.*, **4**(Nov.), p. 100082.
- [73] Xie, Z., Avila, R., Huang, Y., and Rogers, J. A., 2020, "Flexible and Stretchable Antennas for Biointegrated Electronics," *Adv. Mater.*, **32**(15), pp. 1–16.
- [74] Song, J. W., Ryu, H., Bai, W., Xie, Z., Vázquez-Guardado, A., Nandoliya, K., Avila, R., et al., 2023, "Bioresorbable, Wireless, and Battery-Free System for Electrotherapy and Impedance Sensing at Wound Sites," *Sci. Adv.*, **9**(8), pp. 1–12.
- [75] Liu, J., Liu, N., Xu, Y., Wu, M., Zhang, H., Wang, Y., Yan, Y., et al., 2024, "Bioresorbable Shape-Adaptive Structures for Ultrasonic Monitoring of Deep-Tissue Homeostasis," *Science* (1979), **383**(6687), pp. 1096–1103.
- [76] Teng, L., Ye, S., Handschuh-Wang, S., Zhou, X., Gan, T., and Zhou, X., 2019, "Liquid Metal-Based Transient Circuits for Flexible and Recyclable Electronics," *Adv. Funct. Mater.*, **29**(11), pp. 1–9.
- [77] Hwang, S. W., Lee, C. H., Cheng, H., Jeong, J. W., Kang, S. K., Kim, J. H., Shin, J., et al., 2015, "Biodegradable Elastomers and Silicon Nanomembranes/Nanoribbons for Stretchable, Transient Electronics, and Biosensors," *Nano Lett.*, **15**(5), pp. 2801–2808.
- [78] Zhao, Z., Avila, R., Bai, D., Xia, D., She, E., Huang, Y., Rogers, J. A., and Xie, Z., 2024, "A Mechanics and Electromagnetic Scaling Law for Highly Stretchable Radio Frequency Electronics," *J. Mech. Phys. Solids*, **191**, p. 105784.
- [79] McDonald, S. M., Yang, Q., Hsu, Y. H., Nikam, S. P., Hu, Z., Wang, Z., Asheghali, D., et al., 2023, "Resorbable Barrier Polymers for Flexible Bioelectronics," *Nat. Commun.*, **14**(1), p. 7299.
- [80] Sasaki, K., Porter, E., Rashed, E. A., Farrugia, L., and Schmid, G., 2022, "Measurement and Image-Based Estimation of Dielectric Properties of Biological Tissues—Past, Present, and Future," *Phys. Med. Biol.*, **67**(14), p. 14TR01.
- [81] Yang, Q., Liu, T. L., Xue, Y., Wang, H., Xu, Y., Emon, B., Wu, M., et al., 2022, "Ecoresorbable and Bioresorbable Microelectromechanical Systems," *Nat. Electron.*, **5**(8), pp. 526–538.
- [82] Yoon, H. J., Lee, G., Kim, J. T., Yoo, J. Y., Luan, H., Cheng, S., Kang, S., et al., 2022, "Biodegradable, Three-Dimensional Colorimetric Fliers for Environmental Monitoring," *Sci. Adv.*, **8**(51), pp. 1–11.
- [83] Cai, L., Burton, A., Gonzales, D. A., Kasper, K. A., Azami, A., Peralta, R., Johnson, M., et al., 2021, "Osseosurface Electronics—Thin, Wireless, Battery-Free and Multimodal Musculoskeletal Biointerfaces," *Nat. Commun.*, **12**(1), pp. 1–12.
- [84] Bo, R., Xu, S., Yang, Y., and Zhang, Y., 2023, "Mechanically-Guided 3D Assembly for Architected Flexible Electronics," *Chem. Rev.*, **123**(18), pp. 11137–11189.