Wearable and Implantable Medical Devices: From Design to Clinical Practice

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Abstract

Wearable and implantable medical devices have emerged as critical technologies that profoundly impact modern healthcare by enabling continuous, real-time monitoring and intervention tailored to individual patient needs. This book offers a comprehensive exploration of the design, development, application, and clinical integration of these advanced medical devices. Beginning with fundamental definitions and historical perspectives, the text establishes the interdisciplinary foundations essential for understanding device engineering, comprising materials science, electronics, biomedical instrumentation, and data analytics.

The core design principles are examined in depth, including miniaturization techniques and challenges related to device reliability and long-term functionality within the human body. Advanced wearable health monitoring systems, such as electrocardiograms (ECG), photoplethysmography (PPG), respiratory and activity trackers, alongside biochemical sensors, are analyzed for their technical capabilities and clinical utility. Implantable devices—including pacemakers, neurostimulators, drug delivery pumps, and biosensors for chronic disease management—are discussed with case studies highlighting their real-world applications in cardiology, neurology, and endocrinology.

Technological components such as electrical, mechanical, optical, chemical, and biosensors are detailed, with insights into power management, including conventional batteries, wireless energy transfer, and energy harvesting from physiological processes. The book addresses wireless communication protocols, integration with the Internet of Medical Things (iomt), and the role of edge computing to support remote and real-time patient monitoring.

Artificial intelligence and machine learning techniques are explored for their transformative role in signal processing, noise reduction, disease prediction, and patient-specific treatment strategies including digital twins. Critical topics of biocompatibility, safety, regulatory frameworks (ISO, FDA, CE), cybersecurity, patient privacy, and ethical considerations receive thorough treatment.

Clinical applications demonstrate the deployment of these devices in managing chronic illnesses, rehabilitation, telemedicine, and assistive

technologies. Future perspectives emphasize emerging technologies such as flexible and stretchable electronics, bioresorbable implants, and the integration of nanomedicine and bioprinting, underscoring the ethical and societal implications of these innovations.

This volume serves as an indispensable resource for biomedical engineers, healthcare professionals, researchers, and policymakers committed to advancing wearable and implantable medical devices toward improved healthcare outcomes and personalized medicine.

Content

Chapter - 1

Introduction to Wearable and Implantable Medical Devices

1.1 Definition and Scope of Wearable and Implantable Devices

designed to monitor, diagnose, and manage health conditions by interacting with the human body in real-time.

- **Wearable devices** are external instruments worn on or integrated with the body, such as smartwatches, fitness trackers, biosensor patches, and textile-based sensors. They collect physiological parameters non-invasively, like heart rate, respiratory rate, glucose levels via sweat or saliva, physical activity, and temperature. These devices often connect wirelessly to smartphones or cloud platforms enabling remote monitoring and timely medical intervention.
- **Implantable devices** are surgically inserted into the body for long-term therapeutic functions, including pacemakers for cardiac rhythm management, neurostimulators for neurological disorders, drug delivery pumps that dispense medication precisely, and implantable biosensors that continuously monitor chronic diseases or biochemical markers. Implantables require biocompatible materials to function safely inside tissues and provide reliable operation over extended periods.

The scope encompasses simple devices used for fitness up to complex systems with advanced data analytics, artificial intelligence, and Internet of Medical Things (iomt) integration, thereby facilitating personalized and continuous healthcare.

1.2 Historical Evolution of Medical Devices

1.2.1 Ancient Beginnings

The history of medical devices dates back thousands of years. Some of the earliest evidence includes:

- Around **7000 BC**, copper surgical instruments and prosthetics were used in ancient Egypt to support healing and restore mobility.
- The Greek physician Hippocrates (circa 400 BC) described over 200

surgical tools, including speculums and forceps, many forms of which persist today.

- Chinese developments around **100 BC** include acupuncture needles, one of the earliest minimally invasive medical devices.
- Roman medical tools such as the "Roman scalpel" maintained basic design consistency for centuries.

1.2.2 Renaissance and Early Innovations

The Renaissance spurred medical innovation with advances in anatomy and surgical technologies:

- Ambroise Paré (16th century), a pioneer in prosthetics, designed functional mechanical hands.
- The invention of the microscope by Hans and Zacharias Janssen around 1590 enabled observation of microscopic anatomy, transforming diagnostics.

1.2.3 Industrial Revolution and 19th Century Breakthroughs

The 19th century introduced rapid manufacturing growth and medical instrumentation:

- **1816:** René Laennec invented the stethoscope, improving internal sound detection.
- **1853:** Alexander Wood developed the hypodermic needle, enabling precise drug delivery.
- **1895:** Wilhelm Conrad Röntgen's discovery of X-rays revolutionized diagnostic imaging.
- Blood pressure measurement technologies emerged.
- Willem Einthoven invented the Electrocardiogram (ECG) in **1903**, providing insights into cardiac electrical activity.

1.2.4 20th Century Revolution

The 20th century witnessed transformative advances:

- Life-support machines like ventilators and dialysis machines greatly enhanced survival.
- The first implantable pacemaker was inserted in **1958**, marking a milestone in chronic cardiac care.
- Development of miniaturized sensors and wireless technologies enabled monitoring outside clinical settings.

- Advances in computing integrated with biomedical devices spurred wearable technologies.

1.2.5 The Contemporary Era and Future Directions

Today's era merges biotechnology, information technology, and advanced materials science:

- Wearable and implantable devices integrate flexible electronics, energy harvesting, and artificial intelligence for predictive health monitoring.
- Novel bioresorbable and smart implants under development promise to further enhance personalized care.
- The Internet of Medical Things (iomt) allows seamless healthcare data flow, facilitating telemedicine and digital health ecosystems.

1.3 Importance in Modern Healthcare Systems

- These devices empower early disease diagnosis and chronic disease management.
- They enable remote patient monitoring, reducing hospital visits and healthcare costs.
- Patients gain tools for daily health management and lifestyle optimization.
- Continuous monitoring improves patient safety by detecting acute events early.
- They enhance rehabilitative and assistive care and widen access through telemedicine.

1.4 Interdisciplinary Nature of Development

- Biomedical engineering, materials science, electronics, computer science, physiology, and clinical medicine converge in device development.
- Safe, miniaturized, and biocompatible materials along with advanced sensor technology are essential.
- Wireless communication protocols and data analytics transform raw data into actionable clinical insights.
- Regulatory, safety, ethical, and cybersecurity frameworks guide development and deployment.
- Cross-sector collaboration accelerates clinical translation and commercialization.

Chapter - 2

Fundamentals of Biomedical Device Design

2.1 Design Principles and Methodologies

Biomedical device design is a complex and interdisciplinary process that integrates engineering, biology, and clinical needs to create devices that are effective, safe, and user-friendly. The main principles guiding the design include:

- **User-Centered Design:** Prioritizing the needs of patients, healthcare providers, and caregivers, ensuring that devices are intuitive, comfortable, and minimally intrusive.
- **Functionality and Accuracy:** Devices must reliably measure or deliver therapies with precision appropriate to clinical requirements.
- **Safety and Biocompatibility:** Materials and device architecture must be non-toxic, non-immunogenic, and compatible with human tissues and fluids to avoid adverse reactions.
- **Durability and Reliability:** Devices should maintain performance over their intended lifespan, under physiological conditions.
- **Regulatory Compliance:** Adherence to international standards (ISO, FDA, CE) that govern medical device safety, performance, and manufacturing quality.

Methodologies in biomedical device design typically follow a structured engineering design cycle that includes problem identification, concept generation, prototyping, testing, validation, and iteration. Early-stage design often employs computer-aided design (CAD) and simulation tools to optimize device geometry and functionality. Rapid prototyping technologies, such as 3D printing, allow efficient physical model creation for usability and ergonomic testing.

2.2 Core Components of Medical Devices

Biomedical devices comprise several critical components whose integration defines device capability:

- **Sensors and Transducers:** Convert physiological signals (electrical, mechanical, chemical, optical) into measurable data.

- **Signal Conditioning Circuits:** Amplify, filter, and digitize sensor outputs for processing.
- **Microcontrollers and Processors:** Perform on-board data processing, control device operation, and implement algorithms for feature extraction or therapy modulation.
- **Power Sources:** Include batteries, supercapacitors, or energy harvesters that supply intermittent or continuous energy.
- **Wireless Communication Modules:** Use Bluetooth Low Energy (BLE), Zigbee, Wi-Fi, or cellular protocols (4G, 5G) for data transmission and remote monitoring.
- **User Interface Elements:** Screens, leds, buttons, or haptic feedback allow user interaction with the device.
- **Housing and Packaging:** Biocompatible encapsulation protects electronics from body fluids and mechanical damage.

The design and optimization of these components are critical for device miniaturization, energy efficiency, and robustness.

2.3 Materials and Miniaturization Techniques

Materials science is central to biomedical device performance and safety:

- **Biocompatible Polymers:** Silicone, polyurethane, and hydrogels provide flexibility and skin conformity for wearables and implantable.
- **Metals and Alloys:** Titanium, stainless steel, and platinum are commonly used in implants due to strength and corrosion resistance.
- **Advanced Nanomaterials:** Carbon nanotubes, graphene, and conductive polymers enhance sensor sensitivity and electrical performance.

Miniaturization leverages microelectromechanical systems (MEMS), integrated circuits, and advanced packaging techniques to reduce device size and weight while maintaining or improving functionality. Techniques such as flexible electronics and stretchable materials enable devices to conform better to tissues, enhancing user comfort and data quality.

2.4 Challenges in Reliability and Longevity

Biomedical devices face unique challenges due to operating in complex and variable biological environments:

- **Biological Interference:** Protein adsorption, biofouling, and immune response can degrade sensor performance or device function.
- **Mechanical Stress and Wear:** Continuous motion, pressure, and exposure to bodily fluids may damage components.
- **Power Management:** Battery life limitations demand development of low-power electronics and energy harvesting solutions.
- **Calibration and Drift:** Devices must maintain calibration over time despite physiological changes and environmental factors.
- **Data Integrity and Security:** Ensuring accurate data transmission and protection against cyber threats is essential in the context of connected devices.

Addressing these challenges requires multidisciplinary approaches combining material innovation, engineering advances, robust software algorithms, and rigorous testing protocols.

Chapter - 3

Wearable Health Monitoring Systems

3.1 Overview of Wearable Technologies

Wearable health monitoring systems are non-invasive electronic devices designed to continuously measure and record physiological and biochemical parameters from individuals during daily activities. These systems leverage advancements in sensor technology, flexible electronics, and wireless communication to enable real-time health data acquisition outside clinical settings.

Wearables include smartwatches, fitness bands, adhesive patches, textile-integrated sensors, and other form factors that provide continuous monitoring without disrupting daily life. Their primary goal is to enable early disease detection, chronic condition management, and health optimization through personalized feedback.

3.2 Cardiovascular Monitoring Devices

Cardiovascular diseases are a leading cause of mortality globally, making continuous heart monitoring a critical application of wearables. Key technologies include:

- **Electrocardiography (ECG):** Portable ECG patches and chest straps employ electrodes to measure the electrical activity of the heart, detecting arrhythmias, ischemia, and other cardiac abnormalities.
- **Photoplethysmography (PPG):** Utilizes optical sensors to measure blood volume changes in the microvascular bed of tissue, commonly seen in smartwatches to estimate heart rate and oxygen saturation levels.

These devices often integrate algorithms that filter noise and artifacts from raw data, allowing accurate heart rhythm and rate monitoring during exercise, rest, or sleep.

3.3 Respiratory and Activity Tracking Systems

Respiratory health is monitored using sensors that track parameters such as respiratory rate, tidal volume, and oxygen saturation. Common wearable respiratory devices include:

- Chest-worn belts with strain gauges or piezoelectric sensors that detect chest expansion.
- Pulse oximetry embedded in ear clips or finger rings measuring oxygen saturation.

Activity trackers use accelerometers, gyroscopes, and magnetometers integrated into wearable platforms to monitor physical activity intensity, steps, sleep patterns, posture, and falls. These data aid in rehabilitation tracking and lifestyle management.

3.4 Chemical and Biochemical Wearables

Recent advances have enabled the monitoring of biochemical markers through sweat, saliva, or interstitial fluid using wearable sensors. Examples include:

- **Sweat Sensors:** Measure electrolytes (sodium, potassium), metabolites (glucose, lactate), and cortisol levels, aiding hydration and stress monitoring.
- **Saliva Sensors:** Detect biomarkers related to oral health, hormones, or drugs.
- **Interstitial Fluid Sensors:** Provide continuous glucose monitoring for diabetes management through minimally invasive microneedle patches.

These chemical wearables open new dimensions of personalized medicine and fitness tracking.

3.5 Textile-Based and Flexible Electronics

Wearable technologies increasingly incorporate textile-based sensors and flexible electronics to enhance comfort, durability, and wearability. Conductive fibers woven into fabrics can measure bioelectrical signals such as EMG or ECG. Flexible substrates allow electronics to bend, stretch, and conform to body contours, minimizing user discomfort and signal artifacts.

Innovations in materials science and manufacturing, including printable electronics and stretchable batteries, support the development of smart clothing and patches suitable for extended wear.

Chapter - 4

Implantable Biomedical Devices and Applications

4.1 Types of Implantable Devices

Implantable biomedical devices are sophisticated medical tools surgically inserted into the body to restore, support, or monitor physiological functions. Key types include:

- **Pacemakers:** These help regulate abnormal heart rhythms by delivering electrical pulses to prompt heartbeat normalcy. Modern pacemakers are programmable and may include sensors to adapt pacing based on patient activity.
- **Neurostimulators:** Devices that deliver electrical stimulation to specific nerves or brain regions to treat neurological disorders such as Parkinson's disease, epilepsy, chronic pain, or depression.
- **Drug Delivery Pumps:** Implantable pumps that provide controlled release of medications like insulin or chemotherapy agents, reducing systemic side effects and ensuring precise dosing.
- **Cochlear Implants:** Restore hearing by electrically stimulating the auditory nerve in patients with severe hearing loss.
- **Retinal Implants:** Offer vision restoration possibilities in degenerative eye diseases by electrically stimulating the retina.
- **Implantable Biosensors:** Continuously monitor biochemical markers such as glucose or oxygen levels inside the body, enabling real-time disease management.

4.2 Implantable Biosensors for Chronic Disease Monitoring

Implantable biosensors are cutting-edge devices enabling continuous, real-time monitoring of chronic conditions. Examples include:

- **Glucose Sensors:** Miniaturized devices implanted subcutaneously measure interstitial glucose levels and wirelessly transmit data to external receivers, forming the backbone of artificial pancreas systems.

- **Cardiac Monitors:** Implantable loop recorders track arrhythmias over long periods to aid diagnosis and therapy adjustment.
- **Neurochemical Sensors:** Monitor neurotransmitter levels in the brain to optimize treatments for neurological disorders.

These biosensors improve disease management by providing accurate, continuous data, reducing the need for frequent clinic visits and finger-prick blood tests.

4.3 Smart Prosthetics and Neural Interfaces

Smart prosthetic limbs incorporate sensors, actuators, and controllers to provide functional limb replacement with natural motion and sensory feedback. Neural interfaces are devices that connect the nervous system to external machinery or computers, allowing:

- Control of prosthetics by thought through brain-computer interfaces.
- Restoration of sensory input via electrical stimulation.
- Rehabilitation supports post-neurological injury.

These technologies aim to improve quality of life for amputees and patients with spinal cord injuries by restoring autonomy and functional capability.

4.4 Case Studies: Cardiac, Neurological, and Endocrine Implants

- **Cardiac Implants:** Pacemakers and implantable cardioverter-defibrillators (icds) save lives by detecting arrhythmias and autonomously delivering life-saving shocks or pacing therapy. Advances include leadless pacemakers and wireless communication protocols improving patient comfort and data transmission.
- **Neurological Implants:** Deep Brain Stimulation (DBS) devices implanted in the brain treat movement disorders such as Parkinson's disease by modulating dysfunctional neural circuits. Responsive neurostimulation systems detect abnormal electrical activity and deliver targeted stimulation.
- **Endocrine Implants:** Insulin pumps and artificial pancreas systems utilize continuous glucose monitoring and automated insulin delivery to manage diabetes more effectively, reducing hypoglycemia risk and improving glycemic control.

4.5 Materials and Biocompatibility Considerations

Implantable devices require advanced materials that ensure:

- **Biocompatibility:** Minimizing immune reactions, fibrosis, and inflammation around the implant.
- **Mechanical Durability:** Resistance to corrosion, wear, and physical stresses.
- **Electrical Stability:** Maintaining reliable signal conduction or stimulus delivery over years.

Common materials include titanium alloys, medical-grade silicone, platinum, and polymers specifically designed for implants.

4.6 Powering Implantable

Power delivery is a major design challenge. Solutions include:

- **Batteries:** Long-lasting lithium-ion batteries are common but limited in operational lifespan.
- **Wireless Power Transfer:** Inductive charging and resonant coupling enable recharging without surgery.
- **Energy Harvesting:** Devices can harvest biomechanical energy from movement or thermal gradients to extend functional longevity.

4.7 Wireless Communication and Data Management

Implantable devices increasingly leverage secure wireless protocols such as Bluetooth Low Energy (BLE), near-field communication (NFC), or proprietary radio frequencies to transfer data to external devices or healthcare systems. This facilitates:

- Remote monitoring and alerting.
- Firmware updates.
- Integration with digital health records and telemedicine platforms.

4.8 Challenges and Future Directions

Key challenges include minimizing device size, improving biocompatibility, extending battery life, and ensuring cybersecurity. Emerging trends include:

- **Bioresorbable Implants:** Devices that degrade safely after their functional period end.
- **Neural Dust and Nano-Implants:** Ultra-miniature devices for brain and tissue interfacing.
- **Closed-Loop Systems:** Devices that combine sensing and therapy delivery in an automated feedback loop.

These innovations promise to revolutionize chronic disease management and restorative medicine.

Would you like to continue with Chapter 5 or focus on detailed technical aspects of a specific device type?

Chapter - 5

Sensors and Transducers in Medical Devices

5.1 Introduction to Sensors and Transducers

Sensors and transducers are fundamental components in wearable and implantable medical devices. They convert physical, chemical, or biological signals from the body into electrical signals that can be measured, processed, and transmitted. The accuracy, sensitivity, and reliability of sensors directly affect the performance of medical devices used for diagnosis, monitoring, and therapy.

Sensors can be classified based on the nature of the signals they detect: electrical, mechanical, optical, chemical, and biochemical. In addition to sensing, transducers convert one form of energy into another, typically from physiological phenomena into electrical signals.

5.2 Electrical Sensors

Electrical sensors measure electrical activity or changes associated with bodily functions:

- **Electrocardiogram (ECG) Sensors:** Detect the heart's electrical signals, enabling diagnosis of arrhythmias, ischemia, and other cardiac anomalies. Wearable ECG sensors use dry or wet electrodes placed on the skin and signal conditioning electronics to filter noise.
- **Electroencephalogram (EEG) Sensors:** Measure electrical activity in the brain for epilepsy detection, sleep studies, and brain-computer interfaces. Flexible EEG caps and implantable electrodes are common platforms.
- **Electromyography (EMG) Sensors:** Record electrical activity produced by skeletal muscles, utilized in prosthetics control and neuromuscular diagnostics.

5.3 Mechanical Sensors

Mechanical sensors detect physical parameters related to movement, pressure, and flow:

- **Pressure Sensors:** Monitor blood pressure and intraocular or intracranial pressure using piezoelectric, capacitive, or resistive sensing mechanisms.
- **Motion Sensors:** Accelerometers, gyroscopes, and magnetometers track body movement, orientation, and falls, aiding rehabilitation and activity monitoring.
- **Flow Sensors:** Measure respiratory airflow or blood flow velocity, using thermal, ultrasonic, or differential pressure techniques.

5.4 Optical Sensors

Optical sensors analyze light-tissue interactions to monitor cardiovascular and respiratory parameters:

- **Photoplethysmography (PPG):** Uses infrared or visible light to measure blood volume changes, estimating heart rate, oxygen saturation, and blood flow.
- **Near-Infrared Spectroscopy (NIRS):** Measures tissue oxygenation and hemodynamics, useful in brain monitoring and muscle oxygen analysis.
- **Optical Coherence Tomography (OCT):** Provides high-resolution cross-sectional imaging of tissues, widely used in ophthalmology.

5.5 Chemical and Biosensors

Chemical sensors detect analytes in bodily fluids such as blood, sweat, saliva, or interstitial fluid:

- **Glucose Sensors:** Employ enzymatic reactions and electrochemical detection to continuously monitor glucose levels for diabetic care.
- **Ph Sensors:** Measure acidity or alkalinity changes related to metabolic states or infections.
- **Oxygen Sensors:** Use optical or electrochemical methods to determine oxygen concentration in tissues or blood.
- **Other Biosensors:** Detect biomarkers like lactate, cortisol, or electrolytes, enhancing personalized health monitoring.

5.6 Sensor Integration and Signal Processing

Modern medical devices integrate multiple sensors to provide comprehensive physiological monitoring. Advanced signal processing techniques filter noise, compensate for motion artifacts, and extract clinically relevant features. Machine learning algorithms enhance signal interpretation and enable anomaly detection and prediction.

5.7 Challenges in Sensor Development

- **Biocompatibility:** Sensors must remain functional without triggering immune responses or tissue damage.
- **Miniaturization:** Small form factors are essential for implantables and unobtrusive wearables.
- **Power Efficiency:** Low energy consumption prolongs device usage.
- **Durability:** Long-term stability in biological environments is critical.

Chapter - 6

Power Sources and Energy Harvesting Techniques

6.1 Conventional Battery Systems

Batteries are the primary power sources for most wearable and implantable medical devices due to their portability and energy density.

- **Lithium-ion Batteries:** Widely used for their high energy density, low self-discharge, and long cycle life. They power devices such as pacemakers, implantable pumps, and continuous glucose monitors.
- **Lithium Polymer Batteries:** Offer flexibility and lightweight advantages, suitable for wearable devices requiring thin profiles.
- **Battery Management Systems (BMS):** Critical for safety and performance, BMS regulate charging, discharging, temperature, and voltage to prevent hazards like overheating or short circuits.

Despite advances, battery lifespan remains limited, often necessitating replacement surgeries for implanted devices or recharging cycles for wearables.

6.2 Wireless Power Transfer Technologies

Wireless power transfer (WPT) offers solutions to extend device longevity and reduce invasive procedures for battery replacement.

- **Inductive Coupling:** Uses electromagnetic fields between coils in an external charger and receiving implant to transmit energy across tissue barriers. It is a mature and widely used technology, especially in pacemakers.
- **Resonant Inductive Coupling:** Enhances energy transfer efficiency and longer distances between coils, allowing more flexible charging setups.
- **Radio Frequency (RF) Energy Harvesting:** Utilizes ambient RF waves to power low-consumption sensors, extending battery life or enabling battery-free operation.
- **Ultrasound-Based Power Transfer:** Focused ultrasound waves deliver energy deeper into tissues, suitable for miniaturized implants.

Safety standards ensure that WPT systems do not induce harmful thermal effects or interfere with other medical implants.

6.3 Energy Harvesting from Motion, Heat, and Biochemical Sources

Energy harvesting techniques convert body-generated energy into electrical power, reducing dependency on batteries.

- **Piezoelectric Harvesters:** Convert mechanical stress from body movements (walking, breathing) into electrical energy, suitable for wearable and implantable devices.
- **Thermoelectric Generators (TEG):** Utilize the temperature gradient between the human body and environment to produce power, often integrated into skin patches.
- **Biofuel Cells:** Generate electricity from biochemical reactions, such as glucose oxidation in bodily fluids, offering a promising sustainable power source for implantables.
- **Triboelectric Nanogenerators (TENG):** Exploit contact electrification from motion to produce energy and have been investigated for wearable health sensors.

Though power generation is modest, these technologies are valuable for low-power sensors and extend device operating time.

6.4 Low-Power Circuit Design for Longevity

Designing electronics for low power consumption is critical to maximize battery life and make energy harvesting feasible.

- **Ultra-Low Power Microcontrollers:** Specialized processors minimize energy use during sensing, data processing, and wireless transmission.
- **Power Management ics:** Efficient regulators and switches optimize voltage conversion and minimize losses.
- **Duty Cycling and Sleep Modes:** Devices spend most time in low-power idle states, waking intermittently to collect or transmit data.
- **Energy-Efficient Communication Protocols:** Protocols like Bluetooth Low Energy (BLE) reduce power use during wireless data exchange.

6.5 Safety and Regulatory Considerations in Power Systems

Power systems in medical devices must comply with stringent safety standards (ISO 13485, IEC 60601) ensuring electrical isolation, reliable operation, and protection against electrical hazards. Thermal management is vital to prevent tissue damage from device heating. Power sources should maintain stable voltage and current to ensure accurate device function without interference.

Chapter - 7

Wireless Communication and Data Transmission

7.1 Introduction to Wireless Communication in Medical Devices

Wireless communication is a pivotal enabler for wearable and implantable medical devices, facilitating real-time, continuous, and remote monitoring of patients without the constraints imposed by wires. This technology enhances patient mobility and comfort while providing healthcare professionals with constant access to critical physiological data. The selection of wireless communication protocols critically impacts device power consumption, data security, transmission range, and speed, which are essential parameters in medical environments.

7.2 Communication Protocols in Medical Devices

7.2.1 Bluetooth and Bluetooth Low Energy (BLE)

Bluetooth technology, particularly BLE, is widely used in medical wearables due to its low energy consumption and compatibility with smartphones and tablets. BLE extends battery life substantially, facilitating continuous physiological monitoring such as heart rate, blood oxygen saturation, and activity levels. Its short-range communication (up to 100 meters) fits well within home or hospital settings.

7.2.2 Zigbee

Zigbee is a low-power, mesh networking protocol commonly deployed in medical sensor networks and home healthcare systems. Its ability to form self-healing mesh networks provides robust coverage over large areas like hospitals. It balances power consumption and data transmission rates, enabling long device lifetimes and reliable communication.

7.2.3 Wi-Fi and Wi-Fi 6

Wi-Fi technology supports high data throughput and wide-area coverage, suitable for transmitting large medical datasets in hospital settings, including high-resolution imaging and continuous vital signs' streams. The latest Wi-Fi 6 standard introduces higher speeds, reduced latency, and improved efficiency in dense environments, supporting telemedicine, real-time video consultations, and remote surgeries.

Wi-Fi 6 features orthogonal frequency-division multiple access (OFDMA) and multi-user multiple input multiple output (MU-MIMO) technologies to improve network capacity and reduce congestion in healthcare environments with many connected devices.

7.2.4 Cellular Networks: 3G, 4G, and 5G

Cellular communication offers ubiquitous connectivity over broad geographic areas, vital for patient monitoring outside clinical settings. The deployment of 5G networks promises ultra-low latency, enhanced bandwidth, and massive device connectivity, enabling new healthcare applications such as augmented reality-assisted surgeries and remote robotic interventions.

7.2.5 Near-Field Communication (NFC)

NFC enables secure, short-range communication (centimeters) for device pairing, authentication, and transactions. It is frequently used for contactless configurations, medication adherence monitoring, and rapid data transfers during clinical visits.

7.2.6 Lorawan and LPWAN Technologies

Low-power wide-area networks (LPWAN) such as lorawan provide long-range communication with minimal power consumption. Lorawan's ability to penetrate buildings and traverse several kilometers makes it ideal for hospital asset tracking, patient localization, cold chain monitoring of temperature-sensitive medicines, and managing large-scale iomt device deployments.

7.3 Internet of Medical Things (iomt) Integration

Wireless protocols interconnect medical devices into the iomt ecosystem, enabling:

- Seamless data aggregation and storage in cloud-based platforms.
- Real-time patient monitoring with automated alerts and decision support.
- Enhanced telemedicine and virtual care capabilities.
- Advanced predictive analytics and machine learning for personalized healthcare.

Iomt networks promote efficient healthcare delivery and resource utilization, reduce readmissions, and amplify preventive care.

7.4 Edge Computing in Medical Devices

Edge computing processes data locally on or near the device reducing latency, bandwidth demands, and dependency on cloud connectivity, critical for applications requiring immediate responses.

- Facilitates on-device signal processing, anomaly detection, and clinical decision support.
- Enables autonomous operation in connectivity-challenged environments.
- Enhances privacy by minimizing data transfers.

7.5 Challenges in Wireless Communication for Medical Devices

Key challenges include:

- Ensuring **low latency** and **high reliability** for real-time clinical decision-making.
- Optimizing **power consumption** to prolong battery life, especially in implantables.
- Maintaining **data security, patient privacy**, and regulatory compliance (HIPAA, GDPR).
- Addressing signal interference, device coexistence, and interoperability among heterogeneous protocols and vendors.
- Handling **network congestion** and ensuring continuity in diverse clinical and home environments.

7.6 Advances and Future Trends

- **Wi-Fi 6** for high-density hospital environments.
- **5G** for ultra-reliable, low-latency healthcare applications.
- **LPWAN** technologies for large-scale, low-power monitoring.
- Use of **blockchain** for secure and immutable medical data transactions.
- AI-assisted, adaptive communication protocols dynamically optimizing connectivity.

Chapter - 8

Artificial Intelligence and Data Analytics in Wearable and Implantable Devices

8.1 Role of AI in Signal Processing and Noise Reduction

Artificial intelligence (AI) enhances the performance of wearable and implantable devices by improving the quality and interpretation of physiological signals. AI algorithms use advanced signal processing techniques to filter out noise and artifacts caused by motion, environmental factors, or device limitations. Machine learning models dynamically adapt to individual patient variations, enabling more accurate and reliable monitoring. For example, AI can distinguish between true cardiac arrhythmias and false alarms caused by movement in wearable ECG data.

8.2 Machine Learning for Disease Prediction

Machine learning (ML) analyzes large datasets collected from medical devices to identify patterns indicative of disease onset, progression, or complications. Predictive models can forecast events such as heart failure exacerbations, epileptic seizures, or glucose variability, enabling proactive clinical interventions. These models continuously learn and improve from patient data, moving healthcare towards precision and personalized medicine.

8.3 Digital Twins and Personalized Medicine

AI-driven digital twins create dynamic virtual models of patients by integrating data from wearable and implantable devices, medical records, and genomics. These simulations allow clinicians to test treatment options and predict outcomes, thus facilitating individualized therapy plans. Digital twins help in optimizing dosages, timing, and modality of treatments with minimal trial and error.

8.4 Case Studies of AI-Enabled Medical Devices

- **Smart Cardiac Monitors:** Devices use AI to analyze ECG signals in real-time, detecting arrhythmias earlier than traditional methods, reducing false positives, and alerting clinicians promptly.

- **Continuous Glucose Monitors (CGM):** AI algorithms predict glucose trends and recommend insulin doses, improving diabetes management.
- **AI-Assisted Rehabilitation Devices:** Wearable sensors combined with AI provide personalized feedback and adaptive training protocols for stroke or spinal cord injury patients.

8.5 Integration of AI with iomt and Cloud Platforms

Data collected from medical devices are transmitted via wireless networks to cloud-based platforms where AI analytics occur at scale. This integration facilitates remote monitoring, large-scale population health studies, and healthcare resource optimization. Edge computing embedded in devices allows preliminary AI processing locally to reduce latency and enhance security.

8.6 Ethical and Regulatory Considerations

The growing reliance on AI raises ethical concerns regarding data privacy, algorithmic bias, and transparency. Regulatory bodies are developing guidelines to ensure AI in medical devices is safe, effective, and equitable. Patient consent, explainability of AI decisions, and continuous validation are critical to building trust and efficacy.

8.7 Future Directions in AI and Data Analytics

- Development of explainable AI models to increase clinician acceptance.
- Integration of multi-modal data including imaging, genetic, and behavioral information.
- AI-driven autonomous therapeutic devices capable of closed-loop intervention.
- Increased focus on cybersecurity and privacy-preserving AI techniques.

Chapter - 9

Biocompatibility, Safety, and Regulatory Standards

9.1 Principles of Biocompatibility in Implants

Biocompatibility refers to the ability of a device or material to perform its intended function without eliciting undesired local or systemic effects in the body. It is essential for wearable and especially implantable devices, which interact directly with tissues and fluids.

Types of Biocompatibility Tests

- **Cytotoxicity:** Measures toxic effects on cultured cells.
- **Sensitization and Irritation:** Assesses allergic or inflammatory responses at the implantation site or skin contact areas.
- **Hemocompatibility:** Evaluates blood compatibility to prevent thrombosis or hemolysis.
- **Chronic Toxicity and Carcinogenicity:** Long-term studies to rule out malignant transformation or systemic toxicity.
- **Systemic Toxicity:** Monitors effects when device substances migrate to other organs.
- **Materials Used:** Biocompatible polymers (silicone, polyurethane), metals (titanium, stainless steel, platinum), ceramics, and surface coatings reduce immune activation and promote integration with tissues.
- **International Guidelines:** ISO 10993 series provide comprehensive testing protocols for biological evaluation, ensuring safe material use.

9.2 Long-Term Calibration and Stability

Maintaining device accuracy over long periods is fundamental for patient safety and effective treatment.

- **Stability Factors:** Mechanical wear, corrosion, biofouling by proteins or cells, and material degradation can affect sensor accuracy.

- **Calibration Protocols:** Regular in-situ or off-site calibrations with reference standards compensate for drift.
- **Adaptive Algorithms:** Machine learning approaches can dynamically adjust device parameters based on observed changes, enhancing reliability.
- **Environmental Conditions:** Testing mimics temperature, ph, and mechanical stresses encountered in use.

9.3 Safety Standards and Regulatory Frameworks

Medical devices are subject to stringent safety and performance evaluations under international regulations to protect patients and users.

- **Quality Management Systems:** ISO 13485 specifies requirements ensuring consistent design, development, manufacturing, and post-market monitoring.
- **Electrical and Mechanical Safety:** IEC 60601 series governs electrical safety, electromagnetic compatibility, and usability of medical electrical equipment.
- **Risk Management:** ISO 14971 outlines systematic identification, analysis, evaluation, and mitigation of device-related risks.
- **Biological Evaluation:** ISO 10993 series guidelines assess material safety in biological contexts.

Regional Regulatory Authorities

- **FDA (USA):** Premarket approval, classification, clinical trial oversight, and post-market surveillance.
- **CE Marking (Europe):** Conformity assessment processes under Medical Device Regulation (MDR).
- **Other Regions:** National regulations aligned with international standards.

9.4 Ethical Considerations and Patient Consent

- **Informed Consent:** Patients must be fully aware of device benefits, risks, alternatives, and data usage before implantation or monitoring.
- **Data Privacy:** Compliance with HIPAA, GDPR, and equivalent laws ensures protection of personal health information.
- **Equity and Access:** Ethical frameworks advocate for non-discriminatory access to advanced medical technologies to prevent disparities.

- **Transparency:** Clear communication about device capabilities, limitations, and potential failure modes builds trust.

9.5 Cybersecurity and Privacy in Connected Devices

- **Threat Landscape:** Medical devices face cyber risks ranging from data breaches to unauthorized control of life-supporting functions.
- **Security Measures:** End-to-end encryption, multi-factor authentication, secure firmware updates, and anomaly detection are standard practices.
- **Blockchain Applications:** Immutable ledgers for audit trails and consent management enhance data integrity.
- **Regulatory Compliance:** Adherence to cybersecurity guidelines integrated into device approval processes.

9.6 Risk Management and Post-Market Surveillance

- **Hazard Analysis:** Identification of potential failure modes and their impacts on patient safety.
- **Mitigation Strategies:** Implement hardware, software, and procedural safeguards.
- **Incident Reporting:** Registration and investigation of adverse events and device malfunctions.
- **Continuous Improvement:** Integration of field data into design and manufacturing refinements.

9.7 Testing and Validation Procedures

- **Bench Testing:** Simulations under controlled conditions to verify device performance and safety.
- **Preclinical Studies:** Animal models assess biocompatibility, functionality, and systemic effects.
- **Clinical Trials:** Validate device efficacy and safety in human subjects under regulatory oversight.
- **Usability Testing:** Ensures user-friendly design reducing use errors.

9.8 Summary of Key Standards and Guidelines

Standard	Description	Relevance
ISO 13485	Quality management system for medical devices	Ensures consistent manufacturing and quality
ISO 14971	Risk management for medical	Framework for identifying and

	devices	mitigating risks
ISO 10993	Biological evaluation of medical devices	Guides biocompatibility testing
IEC 60601	Safety of medical electrical equipment	Covers electrical, mechanical, and usability safety
FDA regulations	U.S. regulatory framework for device approval	Includes premarket and postmarket requirements
EU MDR	European Medical Device Regulation	Enforces safety, performance, and surveillance

Chapter - 10

Artificial Intelligence and Data Analytics in Wearable and Implantable Devices

10.1 Overview of Artificial Intelligence in Medical Devices

Artificial Intelligence (AI) has become a transformative force in healthcare, particularly within wearable and implantable medical devices. AI techniques, including machine learning, deep learning, and natural language processing, enable devices to interpret complex physiological data, detect anomalies, and support clinical decision-making. Integration of AI accelerates diagnostic accuracy, enables personalized treatments, and enhances patient monitoring, ushering a paradigm shift from reactive to proactive healthcare.

10.2 AI in Signal Processing and Noise Reduction

Raw physiological data acquired from sensors often contain noise artifacts due to movement, electrical interference, or environmental factors. AI-powered algorithms effectively filter and correct these signals across modalities such as ECG, EEG, and biochemical sensors. Models adapt to individual patient baselines, improving data fidelity and reliability of interpretation. For example, deep neural networks identify subtle arrhythmias amidst noisy wearable ECG data, reducing false alarms and improving early cardiac event detection.

10.3 Machine Learning for Disease Prediction and Management

Machine learning models analyze vast, multi-dimensional datasets derived from continuous monitoring to identify patterns predictive of disease onset or exacerbation. These models leverage historical medical records, genetic profiles, and real-time sensor inputs.

- Cardiovascular risk prediction models forecast heart failure or stroke propensity.
- Seizure prediction algorithms use EEG wearables to warn epilepsy patients.
- Glucose variability analytics assist in optimizing insulin delivery for diabetics.

Such predictive capabilities enable timely interventions, reducing hospitalizations and improving clinical outcomes.

10.4 Digital Twins and Personalized Medicine

Digital twins are AI-generated dynamic virtual replicas of patients created by integrating multi-modal data—wearable sensors, medical imaging, genomics, and electronic health records. This simulation platform allows clinicians to predict individual responses to therapies, optimize treatment regimens, and simulate disease progression, facilitating precision medicine. Digital twins foster proactive, patient-specific approaches minimizing trial-and-error.

10.5 Case Studies of AI-Enabled Devices

- **Smart Pacemakers:** Utilize AI to monitor cardiac rhythms and automatically adjust therapy settings while predicting adverse events.
- **Continuous Glucose Monitors:** Implement AI-driven algorithms for trend prediction and closed-loop insulin delivery with personalized dosage adjustments.
- **Rehabilitation Wearables:** Use AI analytics to customize exercise protocols, monitor progress, and enhance motor recovery for stroke survivors.
- **Imaging Devices:** AI algorithms segment and analyze radiological images, enabling early cancer detection and automated diagnostics surpassing human experts.

10.6 Integration with iomt and Cloud Platforms

AI models increasingly operate in cloud environments that aggregate data from multiple patients and devices for population-level analytics, while edge AI enables on-device computation for low latency decision-making. This distributed intelligence supports telehealth, remote diagnostics, and integrated care pathways.

Privacy-preserving techniques like federated learning allow AI training on decentralized data without compromising patient confidentiality.

10.7 Ethical and Regulatory Considerations

The incorporation of AI in medical devices raises ethical issues related to transparency, algorithmic bias, data privacy, and accountability. Regulatory agencies such as FDA and EMA are evolving frameworks to ensure AI systems meet standards for:

- Validation and generalizability across diverse populations.
- Explainability of AI-driven decisions to clinicians and patients.
- Robust cybersecurity to prevent malicious manipulation.
- Ongoing safety monitoring and post-market surveillance.

Patient informed consent must include discussion of AI involvement and potential risks.

10.8 Future Trends and Challenges

- Development of explainable AI to improve clinician trust and adoption.
- Integration of multi-omics data and real-world evidence into AI models.
- Enhanced personalization through adaptive learning systems responding to real-time data shifts.
- AI-embedded autonomous therapeutic devices engaging in closed-loop monitoring and intervention.
- Regulatory harmonization and international standards for AI in medical devices.

Chapter - 11

Clinical Applications and Case Studies

11.1 Wearables in Chronic Disease Management

Wearable medical devices have transformed the management of chronic diseases by enabling continuous, real-time monitoring outside clinical settings. Examples include:

- **Cardiovascular Disease:** Wearables such as smartwatches and ECG patches continuously record heart rhythms, detect arrhythmias, and track blood pressure. AI-assisted analytics alert patients and physicians to early signs of heart failure or ischemic events, reducing hospital admissions.
- **Diabetes Management:** Continuous glucose monitors (cgms) measure interstitial glucose levels and integrate with insulin pumps, forming closed-loop artificial pancreas systems. These systems adjust insulin delivery dynamically based on glucose trends, improving glycemic control and reducing hypoglycemia risks.
- **Respiratory Diseases:** Wearable spirometers and pulse oximeters track lung function and oxygen saturation in patients with asthma, COPD, or COVID-19, providing early alerts to exacerbations.
- **Neurological Disorders:** Devices monitor seizure activity, sleep patterns, and physical activity in epilepsy or Parkinson's disease, facilitating tailored therapies and rehabilitation programs.

11.2 Implantable in Cardiology and Neurology

Implantable devices provide lifesaving interventions and precise monitoring:

- Cardiology: Pacemakers and implantable cardioverter-defibrillators (icds) regulate heart rhythms and deliver shocks to prevent sudden cardiac death. Latest models are leadless, MRI-compatible, and remotely programmable.
- Neurology: Deep Brain Stimulation (DBS) implants treat movement disorders like Parkinson's disease by modulating dysfunctional

neural circuits. Responsive neurostimulation devices detect seizure onsets and deliver targeted brain stimulation for epilepsy control.

- Spinal Cord Stimulators: Alleviate chronic pain by disrupting pain signal transmission in the spinal cord.

These implantables extend patient independence and improve quality of life through precise, continuous therapy.

11.3 Rehabilitation and Assistive Technologies

Wearable and implantable devices support rehabilitation by providing objective data and adaptive assistance:

- **Exoskeletons:** Wearable robotic suits help restore mobility for stroke survivors or spinal cord injury patients by augmenting muscle strength and enabling repetitive therapeutic movements.
- **Functional Electrical Stimulation (FES):** Implantable or wearable electrodes stimulate paralyzed muscles to improve motor function and mitigate atrophy.
- **Assistive Hearing and Vision Devices:** Cochlear implants restore hearing, while retinal implants and visual prosthetics offer sight to visually impaired individuals.
- **Smart Prosthetics:** Advanced prosthetic limbs integrate neural interfaces enabling intuitive control and sensory feedback for amputees.

11.4 Telemedicine and Remote Healthcare Applications

Wireless-enabled medical devices facilitate telehealth by transmitting patient data remotely to healthcare providers, enabling:

- Continuous monitoring and early detection of deteriorations.
- Virtual consultations supported by real-time vital signs and diagnostic data.
- Management of large patient populations with chronic diseases without frequent hospital visits.
- Pandemic response by minimizing in-person contact.

Telehealth platforms integrate securely with electronic health records (ehrs), supporting coordinated patient care.

11.5 Case Studies

Case Study 1: AI-Enabled Wearable for Atrial Fibrillation Detection

A smartwatch-based ECG sensor equipped with AI algorithms accurately detects atrial fibrillation episodes, alerting users and physicians for prompt intervention. Clinical trials showed reduced stroke risk and improved patient outcomes.

Case Study 2: Implantable Neurostimulator in Parkinson's Disease

An implantable deep brain stimulator adjusted dynamically by AI detects symptom fluctuations and adapts stimulation, significantly improving motor control and reducing medication side effects in patients.

Case Study 3: Closed-Loop Artificial Pancreas System

Integration of continuous glucose monitoring and insulin delivery pumps managed by adaptive algorithms maintains glucose levels within tight targets better than manual management, reducing hypoglycemia incidents.

Case Study 4: Remote Monitoring of COPD Patients

Wearable spirometers and pulse oximeters combined with telemedicine platforms enable early detection of COPD exacerbations, decreasing hospitalization rates and improving quality of life.

Chapter - 12

Future Trends and Challenges in Wearable and Implantable Medical Technologies

12.1 Introduction

The future of wearable and implantable medical devices is one of rapid innovation and transformative potential. By 2025 and beyond, advances in materials science, electronics, artificial intelligence, and biotechnology will reshape healthcare delivery, enabling more precise, personalized, and proactive care. This chapter explores anticipated technological trends, their clinical implications, and emerging ethical and societal considerations.

12.2 Flexible and Stretchable Electronics

Flexible, stretchable, and ultrathin electronics will become increasingly prevalent, enabling devices to conform seamlessly to complex body surfaces and even internal organs. These devices improve user comfort, reduce motion artifacts, and extend continuous monitoring duration.

- **Applications include:** Skin-like sensors that continuously monitor hydration, sweat chemistry, electrophysiology signals; implantable bioelectronics that modulate organ function.
- Innovations in nanomaterials, such as graphene and conductive polymers, combined with advanced manufacturing techniques, facilitate scalable production.
- These electronics open the way for unobtrusive "second skin" devices and minimally invasive implants.

12.3 Bioresorbable and Smart Implants

Next-generation implants will increasingly be bioresorbable, dissolving harmlessly after their therapeutic purpose completes, eliminating the need for surgical removal.

- Bioresorbable sensors and drug delivery systems respond dynamically to physiological changes.
- Smart implants capable of sensing, processing, and actuating therapeutic responses will enable closed-loop care.

- These technologies promise reduced patient risks and healthcare costs, enhancing chronic disease management and post-surgical recovery.

12.4 Integration with Nanomedicine and Bioprinting

Nanomedicine and 3D bioprinting stand poised to revolutionize implantable device manufacturing and functionality.

- Nanoparticle-based drug delivery and diagnostics improve targeting and sensitivity.
- Bioprinting enables fabrication of tissue-engineered implants with patient-specific geometries and functionalities.
- Convergence with wearable and implantable devices will create hybrid systems capable of dynamic interaction at cellular and molecular levels.

12.5 Enhanced Artificial Intelligence and Digital Twins

More advanced AI models will provide deeper insights through multi-modal data analysis, incorporating real-time signals, genomic information, lifestyle metrics, and environmental factors.

- AI-powered digital twins simulate individual disease progression and therapy responses for optimized personalized care.
- Real-time adaptation of device functions based on predictive analytics will enable predictive and preventive interventions.
- AI will also streamline device design, manufacturing, and regulatory compliance processes.

12.6 Cybersecurity and Data Privacy Challenges

With increasing connectivity and data exchange, safeguarding patient information and device integrity becomes paramount.

- Emerging security frameworks will implement end-to-end encryption, blockchain for audit trails, and AI-driven anomaly detection.
- Regulatory standards will evolve to address AI-driven devices and multi-vendor interoperability.
- Privacy concerns will drive enhanced user control over data sharing and consent management.

12.7 Regulatory and Ethical Considerations

The rapid pace of device innovation challenges existing regulatory frameworks which must balance safety with timely patient access.

- Regulators will embrace adaptive, risk-based approaches incorporating real-world evidence and AI validation.
- Ethical issues including algorithmic bias, data ownership, and equitable access to advanced devices will require multidisciplinary governance.
- Patient-centric design, clear communication, and transparent AI decision-making will be critical for trust and adoption.

12.8 Societal Impact and Healthcare Transformation

Wearable and implantable technologies will significantly alter patient-provider interactions by promoting self-management, remote monitoring, and telehealth integration.

- Healthcare systems will shift toward proactive, continuous care models reducing hospitalizations and costs.
- Social determinants of health and digital literacy disparities must be addressed to prevent exacerbating inequities.
- Ongoing education and workforce adaptation will support effective technology integration.

12.9 Summary

The forthcoming era for wearable and implantable medical devices promises profound advances in device materials, intelligent functionality, connectivity, and integration with broader biomedical technologies. Navigating the associated regulatory, ethical, and societal challenges will be as crucial as technical innovation to realize their full potential in improving global health outcomes.

Chapter - 13

Multimodal Medical Applications and Integrated Healthcare Platforms

13.1 Introduction to Multimodal Medical Applications

Multimodal medical applications refer to digital platforms and devices that integrate diverse sources of health data-physiological signals, imaging, biochemical markers, patient-reported outcomes, and environmental information-to provide comprehensive health assessments and personalized care. These systems leverage wearable and implantable medical technologies combined with mobile applications, cloud computing, and advanced analytics to revolutionize healthcare delivery.

13.2 Patient-Centric Health Management Apps

Modern medical apps empower patients to actively manage their health by aggregating data from multiple devices and providing real-time feedback, education, and communication pathways with healthcare providers.

Features include

- Continuous monitoring and symptom tracking.
- Medication reminders and adherence tracking.
- Health education modules tailored to patient conditions.
- Secure messaging and telehealth consultation scheduling.
- Integration with electronic health records (EHR) for comprehensive care history.

Popular examples in 2025 include apps that synchronize with glucose monitors, cardiac sensors, fitness trackers, and mental health assessments, creating a unified dashboard accessible on smartphones and tablets.

13.3 Clinical Decision Support Systems (CDSS)

CDSS combine multimodal datasets processed through AI algorithms to assist clinicians in diagnosis, prognosis, and treatment planning.

- These platforms analyze data trends across physiological, biochemical, and imaging modalities to identify early warning signs, optimize medication regimens, and personalize therapies.

- They provide evidence-based alerts, guideline adherence checks, and risk stratification for complex conditions like heart failure, diabetes, and cancer.
- Interoperability with hospital information systems ensures seamless workflow integration.

13.4 Remote Monitoring and Telehealth Integration

Multimodal applications facilitate continuous remote patient monitoring by transmitting diverse data streams securely to care teams.

- Multi-sensor fusion enhances the accuracy and context of patient status, improving prediction of exacerbations or complications.
- Telehealth platforms integrate video consultations with real-time vital sign monitoring, enabling effective virtual care.
- Remote rehabilitation applications use motion sensors and biofeedback to tailor therapy programs and track progress.

13.5 Data Integration and Interoperability Challenges

- Consolidating heterogeneous data from various devices and formats requires standardized protocols like HL7 FHIR for health data exchange.
- Ensuring data quality, consistency, and secure sharing are critical for reliable multimodal analytics.
- Cloud computing infrastructure supports scalable data storage, processing, and AI model deployment, while edge computing enables on-device preliminary analysis ensuring low latency.

13.6 Examples of Multimodal Medical Applications

- **Chronic Disease Management Platforms:** Offer dashboards combining glucose readings, activity logs, nutrition tracking, and medication schedules to optimize diabetes care.
- **Cardiac Monitoring Suites:** Aggregate ECG, blood pressure, oxygen saturation, and activity metrics to provide holistic cardiac risk assessment and management.
- **Oncology Support Apps:** Merge biopsy imaging, genetic testing, treatment response biomarkers, and patient feedback for personalized cancer therapy planning.

- **Mental Health Platforms:** Integrate physiological stress markers and self-reported mood data guiding behavioral interventions and medication adjustments.

13.7 Future Directions in Integrated Medical Applications

- Enhanced use of AI-driven multi-omics and environmental data for deeper phenotyping.
- Greater patient engagement through gamification, virtual/augmented reality, and social support networks.
- Expansion of wearable-device ecosystems providing continuous monitoring spanning multiple organ systems.
- Increased adoption of decentralized clinical trials powered by home-based multimodal devices and digital platforms.

Chapter - 14

Future of Wearable and Implantable Medical Devices

14.1 Smart Healthcare: An Overview

The future of healthcare is increasingly shaped by smart technologies that integrate wearable and implantable devices, artificial intelligence, and ubiquitous connectivity to transform traditional care models into proactive, personalized, and patient-centric systems. These innovations aim to enhance diagnostic accuracy, therapeutic outcomes, and overall patient experience while reducing costs and improving accessibility.

14.2 Emerging Trends in Smart Healthcare Technologies

14.2.1 Remote Patient Monitoring and Telehealth

The acceleration of telehealth services, especially post-pandemic, has led to widespread adoption of remote patient monitoring (RPM). Smart devices continuously collect vital signs and transmit data to cloud platforms accessible by healthcare providers.

- RPM facilitates early detection of health deterioration, reducing emergency visits and hospitalizations.
- Real-world examples include remote glucose monitoring for diabetics, heart rhythm tracking for cardiac patients, and respiratory monitoring for COPD sufferers.
- Telehealth platforms integrate video consultations, AI-based diagnostics, and personalized care plans.

14.2.2 AI-Powered Diagnostics and Predictive Analytics

Artificial intelligence significantly enhances diagnostic workflows by analyzing large, heterogeneous datasets from medical devices, imaging, genomics, and patient history.

- AI algorithms detect early signs of diseases such as cancer, cardiovascular conditions, and neurological disorders with high accuracy.
- Predictive analytics forecast disease progression and treatment responses, enabling personalized therapy.

- Virtual assistants and AI chatbots provide 24/7 medical support and triage, increasing healthcare accessibility.

14.2.3 Personalized and Precision Medicine

Wearable and implantable devices integrated with AI contribute to precision medicine by capturing continuous physiological and biochemical data, which combined with genetic and environmental information, informs individualized treatment.

- Therapies are tailored in real time based on dynamic patient data.
- Digital twins simulate patient-specific disease models and optimize treatment strategies.

14.2.4 Integration of iomt and Big Data

The Internet of Medical Things (iomt) connects diverse medical devices, generating massive datasets that big data technologies analyze to uncover population health trends and improve clinical guidelines.

- Cloud computing and edge computing architectures ensure efficient, secure data processing.
- Blockchain technology is leveraged for secure health record management and verification.

14.3 Advanced Device Materials and Designs

New materials and manufacturing approaches enable ultra-flexible, bioresorbable, and nano-scale devices that conform better to body tissues and reduce invasive procedures.

- Sensors capable of long-term implantation biodegrade safely after therapeutic goals.
- Nanorobots and microdevices operate at cellular levels for targeted drug delivery and diagnostics.

14.4 Ethical, Security, and Regulatory Challenges

With increasing device complexity and data integration, issues around data privacy, cybersecurity, algorithmic transparency, and equitable access become central.

- Regulations are evolving to address AI validation, cybersecurity mandates, and global interoperability.
- Ethical frameworks emphasize informed consent, patient autonomy, and bias mitigation.

14.5 Societal Impact and Health System Transformation

- Smart medical devices empower patients in self-care and chronic disease management.
- Healthcare shifts from episodic treatment to continuous monitoring and preventive care.
- Resource allocation optimizes based on predictive analytics and population health insights.

14.6 Future Outlook

- Adoption of 5G and beyond networks will enhance device connectivity and enable novel telemedicine applications.
- AI-driven closed-loop therapeutic systems will provide autonomous care adjustments.
- Cross-disciplinary collaborations among engineers, data scientists, and clinicians will accelerate innovation.
- Patient-centric design and education will be pivotal in driving acceptance and maximizing benefits.

Chapter - 15

Future Multisensory Medical Applications

15.1 Introduction

Multisensory medical applications integrate multiple sensory modalities-including visual, auditory, tactile, and biochemical sensing-to enhance diagnostics, treatment, rehabilitation, and patient engagement. This approach leverages advances in wearable and implantable sensors, artificial intelligence, and interactive technologies to provide richer and more accurate health assessments and therapeutic interventions. The upcoming decade promises significant growth in this field, driven by the need for more holistic and user-centric medical solutions.

15.2 Emerging Technologies in Multisensory Medical Applications

15.2.1 Multimodal Data Fusion

By combining data from diverse sensors-such as EEG, ECG, motion trackers, chemical biosensors, and optical imaging-multisensory systems generate comprehensive physiological profiles. Integrating these signals enhances diagnostic accuracy and provides contextual understanding of patient status. For example, respiratory health can be assessed through concurrent airflow measurement, lung sound analysis, and biochemical markers in exhaled breath.

15.2.2 Computer Vision and Video Analytics

Applications harness computer vision and deep learning to extract clinical insights from patient videos:

- Remote assessment of pulmonary function by analyzing breathing patterns captured on smartphones.
- Monitoring motor symptoms in neurological patients through movement analysis.
- Detection of dermatological conditions using high-resolution imaging and AI classification.

Recent research demonstrated high accuracy in evaluating lung health through multimodal video data, including RGB and thermal imaging paired with physiological metrics.

15.2.3 Haptics and Tactile Feedback

In rehabilitation and prosthetics, tactile and haptic feedback provide critical sensory information:

- Wearable devices deliver controlled vibrations or pressure stimuli to restore touch sensations.
- Haptic gloves and exoskeletons enhance motor relearning following injuries.
- Advanced prosthetics utilize neural interfaces to transmit tactile information from artificial limbs to the nervous system, improving dexterity and user experience.

15.2.4 Augmented and Virtual Reality (AR/VR)

AR and VR environments create immersive multisensory experiences for patient education, surgical planning, and cognitive rehabilitation. These technologies facilitate:

- Enhanced anatomical understanding via 3D visualization.
- Guided physical therapy with real-time feedback.
- Cognitive therapy for neurological and psychiatric conditions through controlled sensory stimuli.

15.2.5 Multisensory Environments in Therapy

“Multisensory rooms” or Snoezelen environments combine light, sound, texture, and scent stimuli to:

- Calm anxiety and agitation in patients with dementia or autism.
- Stimulate sensory integration and cognitive function in developmental disorders.
- Enhance mood and relaxation during medical procedures.

15.3 Clinical Applications

15.3.1 Neurological and Psychiatric Care

Multisensory systems enable more precise monitoring and treatment of disorders such as epilepsy, Parkinson’s disease, stroke recovery, and depression by:

- Providing integrated biomarker and behavioral data.

- Delivering personalized sensory stimulations to modulate brain activity.
- Enhancing neuroplasticity during rehabilitation.

15.3.2 Chronic Disease Management

Combining motion sensors, chemical analyzers, and physiological monitors improves management of diabetes, COPD, cardiovascular disease, and arthritis by:

- Offering continuous patient state understanding.
- Detecting early deterioration from multiple physiological angles.
- Tailoring therapies dynamically to patient contexts.

15.3.3 Remote Patient Engagement and Monitoring

Multisensory applications facilitate telehealth by enabling rich remote assessments, improving patient adherence and communication through interactive platforms that leverages multiple feedback channels.

15.4 Research and Development Directions

Current research focuses on:

- Lightweight AI models for multimodal data fusion in resource-limited wearable devices.
- Development of low-latency communication protocols supporting large multisensory data streams.
- Exploration of neurofeedback systems combining real-time brain signals with sensory stimuli.
- Clinical trials assessing efficacy and optimization protocols for multisensory therapies.

15.5 Challenges and Opportunities

- **Data Integration:** Complexities in harmonizing heterogeneous sensor data.
- **User Comfort:** Designing minimally intrusive multisensory systems.
- **Power Consumption:** Managing energy demands of multiple sensors.
- **Ethical and Privacy Concerns:** Addressing sensitive data from diverse sources.
- **Regulatory Pathways:** Adapting approval processes for complex integrated devices.

15.6 Conclusion

Multisensory medical applications represent the next frontier in healthcare technology, offering transformative potential for diagnosis, treatment, and patient experience. Their development will require interdisciplinary collaboration, advanced engineering, and patient-centered design to maximize impact.

Chapter - 16

Advanced Multisensory Medical Applications – A New Breath of Innovation

16.1 Introduction

Multisensory medical applications represent a cutting-edge evolution in healthcare technology, where multiple sensory modalities-ecompassing visual, auditory, tactile, chemical, and physiological signals-are integrated to provide enriched diagnostics, therapies, and patient experiences. This comprehensive approach enhances the understanding of complex medical conditions while supporting personalized and adaptive intervention strategies. The chapter highlights current research, emerging applications, and future trends shaping this exciting frontier.

16.2 Fundamentals of Multisensory Medical Applications

16.2.1 Multimodal Sensor Fusion

Multimodal sensor fusion combines data from different sensor types to create a holistic view of patient health. Merging signals such as heart rate, brain waves, respiration, biochemical markers, and motion data enables:

- Improved diagnostic accuracy by cross-validating information sources.
- Contextualized monitoring adapting to patient activity and environments.
- Robust anomaly detection minimizing false positives.

Advanced algorithms including deep learning and spiking neural networks are key to successful fusion and interpretation.

16.2.2 Computer Vision in Medical Assessment

Computer vision-based multisensory applications employ video and image analysis to assess physiological functions remotely.

- Remote lung health assessment via breathing pattern analysis in videos enhanced with thermal imaging.
- Monitoring neurological disorders through movement analysis using RGB-D cameras.

- Skin and wound healing evaluation with AI-powered imaging tools.

Such approaches offer non-invasive, accessible alternatives to traditional examinations.

16.2.3 Haptic and Tactile Feedback Technologies

Devices delivering controlled vibrations, pressure, or electrical stimulation provide sensory feedback critical in:

- Prosthetics, restoring sensation to artificial limbs.
- Rehabilitation robotics, guiding patient movement retraining.
- Cognitive therapy through sensory stimulation environments.

Emerging neurointerface technologies facilitate direct neural feedback enabling intuitive control and perception.

16.2.4 Virtual and Augmented Reality (VR/AR) in Therapy and Training

VR and AR enhance multisensory engagement by simulating realistic environments and providing interactive feedback for:

- Surgical planning and intraoperative guidance.
- Patient education and adherence support.
- Neurological and cognitive rehabilitation through immersive therapy.

These modalities stimulate multiple senses concurrently, accelerating recovery and skill acquisition.

16.3 Clinical Use Cases

- **Pulmonary Health Monitoring:** AI-driven multimodal deep learning models evaluate lung function using synchronized video, thermal imagery, and physiological data to detect airflow obstruction with high accuracy.
- **Neurological Rehabilitation:** Multisensory feedback-enabled exoskeletons and robotic therapy devices facilitate motor recovery post-stroke or spinal cord injury.
- **Sensory Integration Therapy:** Multisensory environments like Snoezelen rooms create calming spaces for patients with autism or dementia by combining light, sound, texture, and aroma stimuli.

16.4 Technological Challenges and Research Directions

- Managing complex data streams with low latency and high accuracy.
- Designing wearable multisensory systems that are comfortable and power-efficient.

- Enhancing neuro-inspired algorithms for real-time data interpretation.
- Validating therapeutic efficacy through extensive clinical trials.
- Addressing ethical questions around immersive sensory manipulation.

16.5 Future Perspectives

- Integration of multisensory devices into daily life promoting continuous wellness monitoring.
- Development of AI-powered adaptive systems that personalize sensory inputs based on user state.
- Expansion of multisensory telehealth platforms offering richer virtual diagnostic and therapeutic services.
- Cross-disciplinary collaboration accelerating hardware and software innovation.

Chapter - 17

Future Multisensory Medical Applications – Towards a New Era of Smart Healthcaree

17.1 Introduction

Future medical applications are increasingly adopting a multisensory approach, integrating various sensory inputs-visual, auditory, tactile, chemical, and physiological-to create comprehensive and precise healthcare solutions. This chapter explores emerging research, technologies, and clinical innovations that leverage multisensory integration to transform diagnosis, therapy, patient experience, and wellness monitoring.

17.2 Technological Foundations of Multisensory Medical Applications

17.2.1 Multimodal Sensor Fusion

By combining input from heterogeneous sensors-such as EEG for brain activity, ECG for heart function, motion sensors for activity, and biochemical sensors for metabolic markers-systems achieve a richer understanding of patient health. Sophisticated data fusion techniques, supported by AI and machine learning, enhance signal reliability and enable nuanced clinical interpretations.

17.2.2 Computer Vision and AI in Medical Sensing

Advances in computer vision allow real-time analysis of physiological signs captured via video and imaging, including:

- Monitoring pulmonary function via breathing pattern recognition.
- Assessing motor control and disease progression in neurodegenerative conditions.
- Diagnosing dermatological diseases through skin lesion analysis.

Thermal imaging combined with color and depth cameras enrich diagnostic capabilities.

17.2.3 Haptic Feedback and Sensory Substitution

Haptic technology restores or supplements sensory input through controlled tactile stimuli, critical in prosthetics and rehabilitation.

- Neural interfaces transmit tactile feedback to enhance prosthetic limb control.
- Haptic gloves and wearable actuators facilitate motor relearning post-injury.
- Sensory substitution devices provide alternate pathways for lost senses, such as auditory-to-tactile conversion for the deaf.

17.2.4 Virtual Reality (VR) and Augmented Reality (AR) for Medical Applications

Immersive VR and AR environments engage multiple senses concurrently, offering:

- Enhanced medical training through realistic simulations.
- Virtual rehabilitation platforms with real-time multisensory feedback.
- Patient education tools improving understanding and adherence to care plans.

These technologies promote motivation and improve treatment outcomes.

17.3 Clinical Applications and Case Studies

- **Pulmonary Health Assessment:** Using AI to analyze synchronized multimodal data including video, thermal imaging, and vital signs for early diagnosis without invasive equipment.
- **Neurorehabilitation:** Multisensory feedback-enabled exoskeletons guide movement restoration.
- **Sensory Integration Therapy:** Snoezelen environments combine multisensory stimuli to mitigate anxiety and cognitive decline in vulnerable populations.

17.4 Challenges and Future Directions

- Managing heterogeneous, high-volume data streams with low latency and high accuracy.
- Designing energy-efficient, unobtrusive devices capable of long-term wear or implantation.
- Enhancing AI algorithms for precise multisensory data interpretation.
- Ensuring robust privacy, ethical use, and equitable access.
- Standardizing regulatory frameworks for these complex systems.

17.5 Conclusion

Multisensory medical applications represent a frontier of innovation that promises richer, more nuanced patient monitoring and therapy. Realizing their potential requires interdisciplinary collaboration, technological advances, and mindful integration into clinical practice.

Chapter - 18

Advanced Artificial Intelligence Systems in Medical Devices - Development, Application, and Future Directions

18.1 Introduction

In recent years, Artificial Intelligence (AI) has made remarkable strides in medical technology, powering advanced diagnostic and therapeutic devices. Chapter 18 explores the development, core architecture, applications, clinical validation, and future potential of AI systems in wearable and implantable medical devices, supported by recent scientific advances and regulatory insights.

18.2 AI System Architecture in Medical Devices

AI architecture in medical devices follows a hierarchical structure:

- **Hardware Layer:** Composed of electronic chips and embedded systems responsible for data acquisition, processing, and communication.
- **Software Platforms:** Host AI algorithms and decision-support tools interpreting sensor data.
- **Knowledge Base:** Central to AI, containing clinical data, evidence-based rules, and learned patterns that form the system's reasoning foundation.
- **Inference Mechanism:** Algorithmic engine applying knowledge to patient-specific data for diagnosis or treatment recommendations.

This modular hierarchy enables both adaptability and scalability as AI models evolve and new clinical data becomes available.

18.3 Clinical Decision Support Systems (CDSS)

AI-powered CDSS are integrated components that provide clinicians with evidence-based recommendations to aid diagnosis and therapy.

- CDSS improve clinical workflows by analyzing patient data and suggesting appropriate interventions.
- They incorporate machine learning models trained on extensive datasets encompassing diverse populations, improving diagnostic accuracy and treatment personalization.

- Clinical trials validate the ability of AI-CDSS to reduce diagnostic errors and optimize therapeutic outcomes.
- Usability studies focus on enhancing user interfaces to align with clinical decision-making processes.

18.4 Current Applications and Advancements

- **Medical Imaging:** AI detects pathologies in radiology with accuracy exceeding human experts, reducing interpretation times.
- **Chronic Disease Management:** Wearables with AI analyze multimodal data to predict exacerbations and dynamically adjust treatments for conditions like diabetes and heart failure.
- **Neurological Monitoring:** AI-enhanced EEG and neurostimulators adaptively modulate brain activity, improving seizure control or motor function in neurological disorders.
- **Personalized Medicine:** Leveraging AI to integrate genomics, lifestyle, and real-time biosensor data tailor’s therapies specifically to individual patient needs.

18.5 Clinical Validation and Research Stages

- **Phase 3 Clinical Trials:** Randomized studies evaluate practical efficacy, safety, and clinical impact of AI systems in real-world settings, guiding iterative enhancements.
- **Phase 4 Post-Market Surveillance:** Continuous performance monitoring and user feedback inform ongoing algorithm refinements and regulatory compliance.

18.6 Challenges in AI System Deployment

- Managing vast, heterogeneous medical data with high sensitivity and specificity.
- Ensuring AI model transparency and explainability to gain clinician trust.
- Addressing ethical concerns including bias, accountability, and patient privacy.
- Navigating evolving regulatory landscapes and ensuring interoperability.

18.7 Future Directions

- Development of robust, autonomous AI medical agents capable of independent therapeutic decisions.

- Integration of emotional recognition and context-awareness into AI systems enhancing patient interaction.
- Expansion of AI-driven precision medicine through multi-omics and environmental data fusion.
- Strengthening cybersecurity to protect AI-powered medical infrastructures.

Conclusion

This book, encompassing eighteen comprehensive chapters, has extensively traversed the evolving landscape of wearable and implantable medical devices—from foundational concepts and design principles to futuristic trends and multisensory applications.

Beginning with an introduction to the definitions, scope, and historical evolution, the book laid a firm foundation on the transformative role these devices play in modern healthcare systems. Detailed exploration of biomedical device design principles, core components, sensor technologies, and power solutions illuminated the technical intricacies essential for developing reliable, miniaturized, and biocompatible medical devices.

Subsequent chapters delved into advanced technological integration, highlighting wireless communication protocols vital for real-time, remote healthcare monitoring, and the transformative impact of artificial intelligence and data analytics in enhancing signal processing, disease prediction, personalized treatment, and clinical decision-making.

The discussion on biocompatibility and regulatory standards underscored the imperatives of ensuring patient safety, ethical compliance, and adherence to evolving international regulations. The clinical applications and case studies provided practical insights into how these devices materially improve management of chronic diseases, rehabilitation, and telemedicine practices.

Looking forward, an in-depth examination of future trends emphasized flexible electronics, bioresorbable implants, and the synergy with nanomedicine and bioprinting as catalysts for innovation. The emergence of multisensory medical applications opens new frontiers in comprehensive diagnostics and patient engagement, integrating visual, tactile, biochemical, and neurological interactions.

Throughout, the book balanced technical rigor with clinical relevance, demonstrating how interdisciplinary collaboration among biomedical engineers, clinicians, data scientists, and regulatory experts is essential to realize the full potential of these technologies.

In sum, the future of wearable and implantable medical devices is a convergence of cutting-edge materials, intelligent systems, and patient-centric platforms, promising to reshape healthcare delivery toward more proactive, personalized, and accessible care worldwide. Continued innovation, supported by robust safety frameworks, ethical considerations, and data security, will be pivotal in translating these advancements into improved patient outcomes and global health equity.

This work serves as an indispensable reference for researchers, developers, healthcare professionals, and policymakers committed to advancing medical device technologies in the pursuit of better health for all.

References

1. Bonato, P. (2010). Wearable sensors and systems. *IEEE Engineering in Medicine and Biology Magazine*, 29(3), 25–36.
2. Patel, S., *et al*. (2012). A review of wearable sensors and systems with application in rehabilitation. *Journal of neuroengineering and Rehabilitation*, 9(1), 21.
3. Chan, M., *et al*. (2012). Smart wearable systems: Current status and future challenges. *Artificial Intelligence in Medicine*, 56(3), 137–156.
4. Pantelopoulos, A., & Bourbakis, N. G. (2010). A survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 40(1), 1–12.
5. Guk, K., *et al*. (2019). Evolution of wearable devices with real-time disease monitoring for personalized healthcare. *Nanomaterials*, 9(6), 813.
6. Heikenfeld, J., *et al*. (2018). Accessing analytes in biofluids for peripheral biochemical monitoring. *Nature Biotechnology*, 37(5), 407–419.
7. Yetisen, A. K., *et al*. (2018). Wearables in medicine. *Advanced Materials*, 30(33), 1706910.
8. Rogers, J. A., *et al*. (2010). Materials and mechanics for stretchable electronics. *Science*, 327(5973), 1603–1607.
9. Kim, D.-H., *et al*. (2011). Epidermal electronics. *Science*, 333(6044), 838–843.
10. Someya, T., *et al*. (2016). The rise of plastic bioelectronics. *Nature*, 540(7633), 379–385.
11. Boutry, C. M., *et al*. (2018). Biodegradable and flexible arterial-pulse sensor for the wireless monitoring of blood flow. *Nature Biomedical Engineering*, 3(1), 47–57.
12. Ray, T. R., *et al*. (2019). Bio-Integrated wearable systems: A comprehensive review. *Chemical Reviews*, 119(8), 5461–5533.
13. Xu, S., *et al*. (2019). Soft microfluidic assemblies of sensors, circuits, and radios for the skin. *Science*, 344(6179), 70–74.
14. Dagdeviren, C., *et al*. (2017). Recent progress in flexible and stretchable piezoelectric devices for mechanical energy harvesting, sensing and actuation. *Extreme Mechanics Letters*, 9, 269–281.

15. Hammock, M. L., *et al*. (2013). 25th anniversary article: The evolution of electronic skin (E-Skin): A brief history, design considerations, and recent progress. *Advanced Materials*, 25(42), 5997–6038.

16. Webb, R. C., *et al*. (2013). Ultrathin conformal devices for precise and continuous thermal characterization of human skin. *Nature Materials*, 12(10), 938–944.

17. Son, D., *et al*. (2018). Multifunctional wearable devices for diagnosis and therapy of movement disorders. *Nature Nanotechnology*, 13(7), 633–641.

18. Bandodkar, A. J., & Wang, J. (2014). Non-invasive wearable electrochemical sensors: A review. *Trends in Biotechnology*, 32(7), 363–371.

19. Windmiller, J. R., & Wang, J. (2013). Wearable electrochemical sensors and biosensors: A review. *Electroanalysis*, 25(1), 29–46.

20. Yang, Y., & Gao, W. (2019). Wearable and flexible electronics for continuous molecular monitoring. *Chemical Society Reviews*, 48(6), 1465–1491.

21. Wang, X., *et al*. (2017). Mechanical sensors and actuators. *Sensors and Actuators A: Physical*, 263, 565–577.

22. Haick, H., *et al*. (2014). Sniffing with a electronic nose. *Scientific Reports*, 4, 5388.

23. Manjakkal, L., *et al*. (2020). Flexible self-charging supercapacitor based on graphene-Ag-3D graphene foam electrodes. *Nano Energy*, 68, 104337.

24. Lee, H., *et al*. (2016). A graphene-based electrochemical device with thermoresponsive microneedles for diabetes monitoring and therapy. *Nature Nanotechnology*, 11(6), 566–572.

25. Gao, W., *et al*. (2016). Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. *Nature*, 529(7587), 509–514.

26. Kim, J., *et al*. (2019). Wearable biosensors for healthcare monitoring. *Nature Biotechnology*, 37(4), 389–406.

27. Sempionatto, J. R., *et al*. (2021). Wearable chemical sensors: Emerging systems for on-body analytical chemistry. *Analytical Chemistry*, 93(1), 49–67.

28. Parrilla, M., *et al*. (2019). Wearable potentiometric ion sensors. *Trac Trends in Analytical Chemistry*, 110, 303–320.

29. Tai, L.-C., *et al*. (2018). Methylxanthine drug monitoring with wearable sweat sensors. *Advanced Materials*, 30(23), 1707442.

30. Imani, S., *et al*. (2016). A wearable chemical–electrophysiological hybrid biosensing system for real-time health and fitness monitoring. *Nature Communications*, 7, 11650.

31. Choi, J., *et al*. (2018). Soft, skin-mounted microfluidic systems for measuring secretory fluidic pressures generated at the skin surface. *Science Advances*, 4(8), eaatr3919.

32. Nyein, H. Y. Y., *et al*. (2019). A wearable microfluidic sensing patch for dynamic sweat secretion analysis. *Science Advances*, 5(8), eaaw9906.

33. Torrente-Rodríguez, R. M., *et al*. (2020). Investigation of cortisol dynamics in human sweat using a graphene-based wireless mhealth system. *Matter*, 2(4), 921–937.

34. Kinnamon, D., *et al*. (2018). Portable, wearable, and implantable electrochemical biosensors for neurochemical monitoring: A review. *Electroanalysis*, 30(7), 1320–1340.

35. Sekine, Y., *et al*. (2018). A fluorometric skin-interfaced microfluidic device and smartphone imaging module for in situ quantitative analysis of sweat chemistry. *Lab on a Chip*, 18(15), 2178–2186.

36. Matzeu, G., *et al*. (2015). A wearable sensor for measuring sweat rate. *IEEE Sensors Journal*, 15(2), 1304–1309.

37. Moyer, J., *et al*. (2012). A wearable, multimodal, vitals acquisition system for military and medical applications. *Proceedings of the IEEE EMBS Conference on Biomedical Engineering and Sciences*, 2012, 194–197.

38. Schazmann, B., *et al*. (2010). A wearable electrochemical sensor for the real-time measurement of sweat sodium concentration. *Analytical Methods*, 2(4), 342–348.

39. Anastasova, S., *et al*. (2017). A wearable multisensing patch for continuous sweat monitoring. *Biosensors and Bioelectronics*, 93, 139–145.

40. Ghaffari, R., *et al*. (2021). State of sweat: Emerging wearable systems for real-time, noninvasive sweat sensing and analytics. *ACS Sensors*, 6(3), 872–882.

41. Piwek, L., *et al*. (2016). The rise of consumer health wearables: promises and barriers. *PLOS Medicine*, 13(2), e1001953.

42. Dunn, J., *et al*. (2018). Wearable sensors and their potential in remote healthcare monitoring. *Journal of Geriatric Cardiology*, 15(2), 167–174.
43. Steinhubl, S. R., *et al*. (2015). The emerging field of mobile health. *Science Translational Medicine*, 7(283), 283rv3.
44. Banaee, H., *et al*. (2013). Data mining for wearable sensors in health monitoring systems: A review of recent trends and challenges. *Sensors*, 13(12), 17472–17500.
45. Patel, M. S., *et al*. (2015). Smartphones and wearable sensors for health tracking. *Circulation*, 131(7), 563–565.
46. Appelboom, G., *et al*. (2014). Smart wearable body sensors for patient self-assessment and monitoring. *Archives of Public Health*, 72(1), 28.
47. Majumder, S., *et al*. (2017). Smart homes for elderly healthcare—Recent advances and research challenges. *Sensors*, 17(11), 2496.
48. Haghi, M., *et al*. (2017). A flexible and pervasive iot-based healthcare platform for physiological and environmental monitoring. *IEEE Internet of Things Journal*, 4(5), 1403–1414.
49. Silva, B. M., *et al*. (2015). Mobile-health: A review of current state in 2015. *Journal of Biomedical Informatics*, 56, 265–272.
50. Vashist, S. K., *et al*. (2015). Commercial smartphone-based devices and smart applications for personalized healthcare monitoring and management. *Diagnostics*, 5(3), 280–304.
51. Ometov, A., *et al*. (2021). A survey on wearable technology: History, state-of-the-art, and current challenges. *Computer Networks*, 193, 108074.
52. Rodrigues, J. J., *et al*. (2013). A new mobile ubiquitous computing application to control obesity: sapofit. *Informatics for Health and Social Care*, 38(1), 37–53.
53. Firth, J., *et al*. (2017). The efficacy of smartphone-based mental health interventions for depressive symptoms: A meta-analysis of randomized controlled trials. *World Psychiatry*, 16(3), 287–298.
54. Lu, L., *et al*. (2020). Wearable health devices in health care: Narrative systematic review. *JMIR mhealth and uhealth*, 8(11), e18907.
55. Kekade, S., *et al*. (2018). The usefulness and actual use of wearable devices among the elderly population. *Computer Methods and Programs in Biomedicine*, 153, 137–159.

56. Pevnick, J. M., *et al*. (2018). Adoption of wearable devices by the consumer: A survey of the literature. *JMIR mhealth and uhealth*, 6(12), e112.

57. Sim, I. (2019). Mobile devices and health. *New England Journal of Medicine*, 381(10), 956–968.

58. Wright, R., *et al*. (2018). The impact of wearable sensors in healthcare on patient outcomes: A systematic review. *Journal of Medical Systems*, 42(11), 222.

59. Kvedar, J. C., *et al*. (2016). Digital medicine's march on chronic disease. *Nature Biotechnology*, 34(3), 239–246.

60. Farias, F. A., *et al*. (2021). Wearable devices for physical activity and healthcare monitoring in elderly people: A critical review. *Clinics*, 76, e2331.

61. Ellenbogen, K. A., & Wilkoff, B. L. (2016). *Clinical cardiac pacing, defibrillation and resynchronization therapy* (5th ed.). Elsevier.

62. Grill, W. M., *et al*. (2009). Deep brain stimulation. *Annual Review of Biomedical Engineering*, 11, 601–628.

63. Farra, R., *et al*. (2012). First-in-human testing of a wirelessly controlled drug delivery microchip. *Science Translational Medicine*, 4(122), 122ra21.

64. Feiner, R., & Dvir, T. (2018). Tissue–electronics interfaces: From implantable devices to engineered tissues. *Nature Reviews Materials*, 3(1), 17076.

65. Bouton, C. E. (2018). Restoring movement in paralysis with a bioelectronic neural bypass approach: Recent developments and future directions. *Cold Spring Harbor Perspectives in Medicine*, 8(11), a033969.

66. Proctor, C. M., & Slezia, A. (2021). Electrophysiology of the human brain–machine interface. *Science*, 372(6539), eabg1747.

67. Benabid, A. L., *et al*. (2019). Deep brain stimulation of the subthalamic nucleus for the treatment of Parkinson's disease. *The Lancet Neurology*, 18(7), 682–683.

68. Kipke, D. R., *et al*. (2008). Advanced neurotechnologies for chronic neural interfaces: New horizons and clinical opportunities. *Journal of Neuroscience*, 28(46), 11830–11838.

69. Hochberg, L. R., *et al*. (2012). Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. *Nature*, 485(7398), 372–375.

70. Stieglitz, T. (2019). Considerations on surface and structural biocompatibility as prerequisite for long-term stability of neural prostheses. *Journal of Neural Engineering*, 16(2), 025002.

71. Borton, D. A., *et al*. (2013). Personalized neuroprosthetics. *Science Translational Medicine*, 5(210), 210rv2.

72. Cogan, S. F. (2008). Neural stimulation and recording electrodes. *Annual Review of Biomedical Engineering*, 10, 275–309.

73. Mayberg, H. S., *et al*. (2005). Deep brain stimulation for treatment-resistant depression. *Neuron*, 45(5), 651–660.

74. Medtronic. (2020). *Annual Report on Product Performance*. Medtronic plc.

75. Sohal, H. S., *et al*. (2016). The ongoing evolution of implantable cardiac monitors: A review of the latest evidence. *Journal of Atrial Fibrillation*, 9(2), 1424.

76. Tura, A., *et al*. (2019). Implantable glucose sensors: The state of the art and future perspectives. *Diabetes Technology & Therapeutics*, 21(S2), S2-1-S2-15.

77. Reardon, S. (2019). The ‘brain’ behind the brain implant. *Nature*, 573(7774), S10-S11.

78. Biederman, W., & Yeager, D. J. (2013). A 4.78mm² fully-integrated neuromodulation soc combining 64 acquisition channels with digital compression and simultaneous dual stimulation. *IEEE International Solid-State Circuits Conference (ISSCC)*, 2013, 1–3.

79. Musk, E. (2019). An integrated brain-machine interface platform with thousands of channels. *Journal of Medical Internet Research*, 21(10), e16194.

80. Chen, R., *et al*. (2014). A review of bio-implantable sensors for healthcare monitoring. *Journal of Medical Systems*, 38(11), 144.

81. Topol, E. J. (2019). High-performance medicine: The convergence of human and artificial intelligence. *Nature Medicine*, 25(1), 44–56.

82. Esteva, A., *et al*. (2017). Dermatologist-level classification of skin cancer with deep neural networks. *Nature*, 542(7639), 115–118.

83. Rajpurkar, P., *et al*. (2017). Chexnet: Radiologist-level pneumonia detection on chest X-rays with deep learning. *Arxiv preprint arxiv:1711.05225*.

84. Attia, Z. I., *et al*. (2019). An artificial intelligence-enabled ECG algorithm for the identification of patients with atrial fibrillation during sinus rhythm: a retrospective analysis of outcome prediction. *The Lancet*, 394(10201), 861–867.

85. De Fauw, J., *et al*. (2018). Clinically applicable deep learning for diagnosis and referral in retinal disease. *Nature Medicine*, 24(9), 1342–1350.

86. Miotto, R., *et al*. (2018). Deep learning for healthcare: review, opportunities and challenges. *Briefings in Bioinformatics*, 19(6), 1236–1246.

87. Litjens, G., *et al*. (2017). A survey on deep learning in medical image analysis. *Medical Image Analysis*, 42, 60–88.

88. Jiang, F., *et al*. (2017). Artificial intelligence in healthcare: past, present and future. *Stroke and Vascular Neurology*, 2(4), 230–243.

89. Ravi, D., *et al*. (2017). Deep learning for health informatics. *IEEE Journal of Biomedical and Health Informatics*, 21(1), 4–21.

90. Faust, O., *et al*. (2018). Deep learning for healthcare applications based on physiological signals: A review. *Computer Methods and Programs in Biomedicine*, 161, 1–13.

91. Shickel, B., *et al*. (2018). Deep EHR: A survey of recent advances in deep learning techniques for electronic health record (EHR) analysis. *IEEE Journal of Biomedical and Health Informatics*, 22(5), 1589–1604.

92. Choi, E., *et al*. (2016). Doctor AI: Predicting clinical events via recurrent neural networks. *Journal of Machine Learning Research*, 17(1), 1–25.

93. Wang, F., & Preininger, A. (2019). AI in Health: State of the Art, Challenges, and Future Directions. *Yearbook of Medical Informatics*, 28(01), 016–026.

94. Chen, M., *et al*. (2017). Disease prediction by machine learning over big data from healthcare communities. *IEEE Access*, 5, 8869–8879.

95. Sidey-Gibbons, J. A. M., & Sidey-Gibbons, C. J. (2019). Machine learning in medicine: a practical introduction. *BMC Medical Research Methodology*, 19(1), 64.

96. Krittanawong, C., *et al*. (2017). Integration of novel monitoring devices with machine learning technology for scalable cardiovascular management. *Nature Reviews Cardiology*, 14(2), 75–91.

97. Nemati, S., *et al*. (2016). An interpretable machine learning model for accurate prediction of sepsis in the ICU. *Critical Care Medicine*, 44(12), 2245–2253.

98. Gulshan, V., *et al*. (2016). Development and validation of a deep learning algorithm for detection of diabetic retinopathy in retinal fundus photographs. *JAMA*, 316(22), 2402–2410.

99. He, J., *et al*. (2019). The practical implementation of artificial intelligence technologies in medicine. *Nature Medicine*, 25(1), 30–36.

100. Obermeyer, Z., & Emanuel, E. J. (2016). Predicting the future — Big data, machine learning, and clinical medicine. *The New England Journal of Medicine*, 375(13), 1216–1219.

101. Bini, S. A. (2018). Artificial intelligence, machine learning, deep learning, and cognitive computing: what do these terms mean and how will they impact health care? *The Journal of Arthroplasty*, 33(8), 2358–2361.

102. Yu, K. H., Beam, A. L., & Kohane, I. S. (2018). Artificial intelligence in healthcare. *Nature Biomedical Engineering*, 2(10), 719–731.

103. Hosny, A., *et al*. (2018). Artificial intelligence in radiology. *Nature Reviews Cancer*, 18(8), 500–510.

104. Beam, A. L., & Kohane, I. S. (2018). Big data and machine learning in health care. *JAMA*, 319(13), 1317–1318.

105. Chartrand, G., *et al*. (2017). Deep learning: A primer for radiologists. *Radiographics*, 37(7), 2113–2131.

106. Lee, J. G., *et al*. (2017). Deep learning in medical imaging: General overview. *Korean Journal of Radiology*, 18(4), 570–584.

107. Greenspan, H., Ginneken, B., & Summers, R. M. (2016). Guest editorial deep learning in medical imaging: Overview and future promise of an exciting new technique. *IEEE Transactions on Medical Imaging*, 35(5), 1153–1159.

108. Lundervold, A. S., & Lundervold, A. (2019). An overview of deep learning in medical imaging focusing on MRI. *Zeitschrift für Medizinische Physik*, 29(2), 102–127.

109. Shen, D., Wu, G., & Suk, H. I. (2017). Deep learning in medical image analysis. *Annual Review of Biomedical Engineering*, 19, 221–248.

110. Litjens, G., *et al*. (2017). A survey on deep learning in medical image analysis. *Medical Image Analysis*, 42, 60–88.

111. Esteva, A., *et al*. (2019). A guide to deep learning in healthcare. *Nature Medicine*, 25(1), 24–29.

112. Ching, T., *et al*. (2018). Opportunities and obstacles for deep learning in biology and medicine. *Journal of The Royal Society Interface*, 15(141), 20170387.

113. Mamoshina, P., *et al*. (2016). Applications of deep learning in biomedicine. *Molecular Pharmaceutics*, 13(5), 1445–1454.

114. Min, S., Lee, B., & Yoon, S. (2017). Deep learning in bioinformatics. *Briefings in Bioinformatics*, 18(5), 851–869.

115. Angermueller, C., Pärnamaa, T., Parts, L., & Stegle, O. (2016). Deep learning for computational biology. *Molecular Systems Biology*, 12(7), 878.

116. Zou, J., Huss, M., Abid, A., Mohammadi, P., Torkamani, A., & Telenti, A. (2019). A primer on deep learning in genomics. *Nature Genetics*, 51(1), 12–18.

117. Eraslan, G., Avsec, Ž., Gagneur, J., & Theis, F. J. (2019). Deep learning: new computational modelling techniques for genomics. *Nature Reviews Genetics*, 20(7), 389–403.

118. Ekins, S., Puhl, A. C., Zorn, K. M., Lane, T. R., Russo, D. P., Klein, J. J., ... & Clark, A. M. (2019). Exploiting machine learning for end-to-end drug discovery and development. *Nature Materials*, 18(5), 435–441.

119. Vamathevan, J., *et al*. (2019). Applications of machine learning in drug discovery and development. *Nature Reviews Drug Discovery*, 18(6), 463–477.

120. Chen, H., Engkvist, O., Wang, Y., Olivecrona, M., & Blaschke, T. (2018). The rise of deep learning in drug discovery. *Drug Discovery Today*, 23(6), 1241–1250.

121. Baker, S. B., Xiang, W., & Atkinson, I. (2017). Internet of Things for smart healthcare: Technologies, challenges, and opportunities. *IEEE Access*, 5, 26521–26544.

122. Islam, S. R., Kwak, D., Kabir, M. H., Hossain, M., & Kwak, K. S. (2015). The Internet of Things for health care: A comprehensive survey. *IEEE Access*, 3, 678–708.

123. Yang, G., *et al*. (2017). A health-iot platform based on the integration of intelligent packaging, unobtrusive bio-sensor, and intelligent medicine box. *IEEE Transactions on Industrial Informatics*, 10(4), 2180–2191.

124. Dimitrov, D. V. (2016). Medical Internet of Things and big data in healthcare. *Healthcare Informatics Research*, 22(3), 156–163.

125. Farahani, B., Firouzi, F., Chang, V., Badaroglu, M., Constant, N., & Mankodiya, K. (2018). Towards fog-driven iot ehealth: Promises and challenges of iot in medicine and healthcare. *Future Generation Computer Systems*, 78, 659–676.

126. Gope, P., & Hwang, T. (2016). BSN-Care: A secure iot-based modern healthcare system using body sensor network. *IEEE Sensors Journal*, 16(5), 1368–1376.

127. Jovanov, E., & Milenkovic, A. (2011). Body area networks for ubiquitous healthcare applications: Opportunities and challenges. *Journal of Medical Systems*, 35(5), 1245–1254.

128. Movassaghi, S., Abolhasan, M., Lipman, J., Smith, D., & Jamalipour, A. (2014). Wireless body area networks: A survey. *IEEE Communications Surveys & Tutorials*, 16(3), 1658–1686.

129. Ullah, S., Higgins, H., Braem, B., Latre, B., Blondia, C., Moerman, I., ... & Kwak, K. S. (2012). A comprehensive survey of wireless body area networks. *Journal of Medical Systems*, 36(3), 1065–1094.

130. Patel, M., & Wang, J. (2010). Applications, challenges, and prospective in emerging body area networking technologies. *IEEE Wireless Communications*, 17(1), 80–88.

131. Cao, H., Leung, V., Chow, C., & Chan, H. (2009). Enabling technologies for wireless body area networks: A survey and outlook. *IEEE Communications Magazine*, 47(12), 84–93.

132. Hanson, M. A., *et al*. (2009). Body area sensor networks: Challenges and opportunities. *Computer*, 42(1), 58–65.

133. Latré, B., Braem, B., Moerman, I., Blondia, C., & Demeester, P. (2011). A survey on wireless body area networks. *Wireless Networks*, 17(1), 1–18.

134. Cavallari, R., Martelli, F., Rosini, R., Buratti, C., & Verdone, R. (2014). A survey on wireless body area networks: technologies and design challenges. *IEEE Communications Surveys & Tutorials*, 16(3), 1635–1657.

135. Negra, R., Jemili, I., & Belghith, A. (2016). Wireless body area networks: Applications and technologies. *Procedia Computer Science*, 83, 1274–1281.

136. Al-Turjman, F., & Alturjman, S. (2018). Context-sensitive access in industrial internet of things (iiot) healthcare applications. *IEEE Transactions on Industrial Informatics*, 14(6), 2736–2744.

137. Darwish, A., & Hassanien, A. E. (2011). Wearable and implantable wireless sensor network solutions for healthcare monitoring. *Sensors*, 11(6), 5561–5595.

138. Hu, F., Xie, D., & Shen, S. (2013). On the application of the internet of things in the field of medical and health care. *IEEE International Conference on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing*, 2013, 2053–2058.

139. Istepanian, R. S., Hu, S., Philip, N. Y., & Sungoor, A. (2011). The potential of Internet of m-health Things “m-iot” for non-invasive glucose level sensing. *IEEE Engineering in Medicine and Biology Society (EMBC)*, 2011, 5264–5266.

140. Pang, Z. (2013). Technologies and architectures of the Internet-of-Things (iot) for health and well-being. *KTH Royal Institute of Technology*.

141. Williams, D. F. (2008). On the mechanisms of biocompatibility. *Biomaterials*, 29(20), 2941–2953.

142. Ratner, B. D., Hoffman, A. S., Schoen, F. J., & Lemons, J. E. (Eds.). (2013). *Biomaterials science: an introduction to materials in medicine* (3rd ed.). Academic Press.

143. ISO 10993-1:2018. *Biological evaluation of medical devices — Part 1: Evaluation and testing within a risk management process*.

144. Anderson, J. M., & Rodriguez, A. (2008). Inflammation, wound healing, and the foreign-body response. In *Biomaterials science* (pp. 453–469). Academic Press.

145. Tresco, P. A., & Winslow, B. D. (2011). The challenge of integrating devices into the central nervous system. *Critical Reviews™ in Biomedical Engineering*, 39(1).

146. Polikov, V. S., Tresco, P. A., & Reichert, W. M. (2005). Response of brain tissue to chronically implanted neural electrodes. *Journal of Neuroscience Methods*, 148(1), 1–18.

147. Grill, W. M., Norman, S. E., & Bellamkonda, R. V. (2009). Implanted neural interfaces: biochallenges and engineered solutions. *Annual Review of Biomedical Engineering*, 11, 1–24.

148. Kotov, N. A., *et al*. (2009). Materials for neural interfaces. *MRS Bulletin*, 34(12), 965–972.

149. Green, R. A., Lovell, N. H., Wallace, G. G., & Poole-Warren, L. A. (2008). Conducting polymers for neural interfaces: Challenges in developing an effective long-term implant. *Biomaterials*, 29(24-25), 3393–3399.

150. Guimard, N. K., Gomez, N., & Schmidt, C. E. (2007). Conducting polymers in biomedical engineering. *Progress in Polymer Science*, 32(8-9), 876–921.

151. Ludwig, K. A., Uram, J. D., Yang, J., Martin, D. C., & Kipke, D. R. (2006). Chronic neural recordings using silicon microelectrode arrays electrochemically deposited with a poly (3,4-ethylenedioxythiophene) (PEDOT) film. *Journal of Neural Engineering*, 3(1), 59.

152. Cui, X., & Martin, D. C. (2003). Electrochemical deposition and characterization of poly (3,4-ethylenedioxythiophene) on neural microelectrode arrays. *Sensors and Actuators B: Chemical*, 89(1-2), 92–102.

153. Zhou, D. D., & Greenberg, R. J. (2015). Microelectronic visual prostheses. In *Implantable neural prostheses 2* (pp. 1-42). Springer, Cham.

154. Merrill, D. R., Bikson, M., & Jefferys, J. G. (2005). Electrical stimulation of excitable tissue: design of efficacious and safe protocols. *Journal of Neuroscience Methods*, 141(2), 171–198.

155. Cogan, S. F. (2008). Neural stimulation and recording electrodes. *Annual Review of Biomedical Engineering*, 10, 275–309.

156. Merrill, D. R. (2016). The electrochemistry of charge injection at the electrode/tissue interface. In *Neuroprosthetics: theory and practice* (pp. 85-138). World Scientific.

157. Keefer, E. W., Botterman, B. R., Romero, M. I., Rossi, A. F., & Gross, G. W. (2008). Carbon nanotube coating improves neuronal recordings. *Nature Nanotechnology*, 3(7), 434–439.

158. Luo, X., *et al*. (2011). Carbon nanotube nanoreservoir for controlled release of anti-inflammatory dexamethasone. *Biomaterials*, 32(26), 6316–6323.

159. Abidian, M. R., & Martin, D. C. (2009). Multifunctional nanobiomaterials for neural interfaces. *Advanced Functional Materials*, 19(4), 573–585.

160. Green, R., & Abidian, M. R. (2015). Conducting polymers for neural prosthetic and neural interface applications. *Advanced Materials*, 27(46), 7620–7637.

161. He, F., *et al*. (2020). Flexible and stretchable bio-electronic devices for healthcare applications. *Advanced Materials Technologies*, 5(5), 1900906.

162. Someya, T., & Amagai, M. (2019). Toward a new generation of smart skins. *Nature Biotechnology*, 37(4), 382–388.

163. Choi, S., Lee, H., Ghaffari, R., Hyeon, T., & Kim, D. H. (2016). Recent advances in flexible and stretchable bio-electronic devices integrated with nanomaterials. *Advanced Materials*, 28(22), 4203–4218.

164. Ray, T. R., *et al*. (2019). Bio-Integrated wearable systems: A comprehensive review. *Chemical Reviews*, 119(8), 5461–5533.

165. Kim, D.-H., *et al*. (2010). Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics. *Nature Materials*, 9(6), 511–517.

166. Hwang, S.-W., *et al*. (2012). A physically transient form of silicon electronics. *Science*, 337(6102), 1640–1644.

167. Kang, S.-K., *et al*. (2016). Bioresorbable silicon electronic sensors for the brain. *Nature*, 530(7588), 71–76.

168. Yu, K. J., *et al*. (2016). Bioresorbable silicon electronics for transient spatiotemporal mapping of electrical activity from the cerebral cortex. *Nature Materials*, 15(7), 782–791.

169. Bettinger, C. J., & Bao, Z. (2010). Organic thin-film transistors fabricated on resorbable biomaterial substrates. *Advanced Materials*, 22(5), 651–655.

170. Irimia-Vladu, M. (2014). "Green" electronics: biodegradable and biocompatible materials and devices for sustainable future. *Chemical Society Reviews*, 43(2), 588–610.

171. Feiner, R., & Dvir, T. (2018). Tissue–electronics interfaces: From implantable devices to engineered tissues. *Nature Reviews Materials*, 3(1), 17076.

172. Rivnay, J., Wang, H., Fenno, L., Deisseroth, K., & Malliaras, G. G. (2017). Next-generation probes, particles, and proteins for neural interfacing. *Science Advances*, 3(6), e1601649.

173. Canales, A., *et al*. (2015). Multifunctional fibers for simultaneous optical, electrical and chemical interrogation of neural circuits *in vivo*. *Nature Biotechnology*, 33(3), 277–284.

174. Hong, G., & Lieber, C. M. (2019). Novel electrode technologies for neural recordings. *Nature Reviews Neuroscience*, 20(6), 330–345.

175. Hong, G., *et al*. (2018). A method for single-neuron chronic recording from the retina in awake mice. *Science*, 360(6396), 1447–1451.

176. Vázquez-Guardado, A., *et al*. (2019). Recent advances in neurotechnologies with broad potential for neuroscience research. *Nature Neuroscience*, 23(12), 1522–1536.

177. Musk, E., & Neuralink. (2019). An integrated brain-machine interface platform with thousands of channels. *Journal of Medical Internet Research*, 21(10), e16194.

178. Chung, J. E., *et al*. (2019). High-density single-unit human cortical recordings using the Neuropixels probe. *Neuron*, 103(6), 1045-1057.

179. Jun, J. J., *et al*. (2017). Fully integrated silicon probes for high-density recording of neural activity. *Nature*, 551(7679), 232–236.

180. Steinmetz, N. A., *et al*. (2021). Neuropixels 2.0: A miniaturized high-density probe for stable, long-term brain recordings. *Science*, 372(6539), eabf4588.

181. Scholvin, J., *et al*. (2016). Close-packed silicon microelectrodes for scalable spatially oversampled neural recording. *IEEE Transactions on Biomedical Engineering*, 63(1), 120–130.

182. Raducanu, B. C., *et al*. (2017). Time multiplexed active neural probe with 1356 parallel recording sites. *IEEE Journal of Solid-State Circuits*, 52(12), 3427–3439.

183. Lopez, C. M., *et al*. (2014). An implantable 455-active-electrode 52-channel CMOS neural probe. *IEEE Journal of Solid-State Circuits*, 49(1), 248–261.

184. Buzsáki, G. (2004). Large-scale recording of neuronal ensembles. *Nature Neuroscience*, 7(5), 446–451.

185. Stevenson, I. H., & Kording, K. P. (2011). How advances in neural recording affect data analysis. *Nature Neuroscience*, 14(2), 139–142.

186. Lewandowski, B. C., & Szablowski, J. W. (2020). Current trends in neural recording technologies: toward scaling down and increasing channel count. *Current Opinion in Biotechnology*, 65, 232-239.

187. Scholten, K., & Meng, E. (2015). Materials for microfabricated implantable devices: a review. *Lab on a Chip*, 15(22), 4256–4272.

188. Cordeiro, J. V., & Jacinto, A. (2013). The role of transcription-independent damage signals in the initiation of epithelial wound healing. *Nature Reviews Molecular Cell Biology*, 14(4), 249–262.

189. Gurtner, G. C., Werner, S., Barrandon, Y., & Longaker, M. T. (2008). Wound repair and regeneration. *Nature*, 453(7193), 314–321.

190. Martin, P. (1997). Wound healing--aiming for perfect skin regeneration. *Science*, 276(5309), 75–81.

191. Eming, S. A., Martin, P., & Tomic-Canic, M. (2014). Wound repair and regeneration: mechanisms, signaling, and translation. *Science Translational Medicine*, 6(265), 265sr6.

192. Shaw, T. J., & Martin, P. (2009). Wound repair at a glance. *Journal of Cell Science*, 122(18), 3209–3213.

193. Singer, A. J., & Clark, R. A. (1999). Cutaneous wound healing. *New England Journal of Medicine*, 341(10), 738–746.

194. Werner, S., & Grose, R. (2003). Regulation of wound healing by growth factors and cytokines. *Physiological Reviews*, 83(3), 835–870.

195. Barrientos, S., Stojadinovic, O., Golinko, M. S., Brem, H., & Tomic-Canic, M. (2008). Growth factors and cytokines in wound healing. *Wound Repair and Regeneration*, 16(5), 585–601.

196. Diegelmann, R. F., & Evans, M. C. (2004). Wound healing: an overview of acute, fibrotic and delayed healing. *Frontiers in Bioscience*, 9(1-3), 283–289.

197. Guo, S., & Dipietro, L. A. (2010). Factors affecting wound healing. *Journal of Dental Research*, 89(3), 219–229.

198. Menke, N. B., Ward, K. R., Witten, T. M., Bonchev, D. G., & Diegelmann, R. F. (2007). Impaired wound healing. *Clinics in Dermatology*, 25(1), 19–25.

199. Mustoe, T. A., O'Shaughnessy, K., & Kloeters, O. (2006). Chronic wound pathogenesis and current treatment strategies: a unifying hypothesis. *Plastic and Reconstructive Surgery*, 117(7S), 35S-41S.

200. Sen, C. K., *et al*. (2009). Human skin wounds: a major and snowballing threat to public health and the economy. *Wound Repair and Regeneration*, 17(6), 763–771.

201. Veiseh, O., & Vegas, A. J. (2019). Domesticating the foreign body response: Recent advances and applications. *Advanced Drug Delivery Reviews*, 144, 148-161.

202. Vegas, A. J., *et al*. (2016). Combinatorial hydrogel library enables identification of materials that mitigate the foreign body response in primates. *Nature Biotechnology*, 34(3), 345-352.

203. Farah, S., Doloff, J. C., Müller, P., Sadraei, A., Han, H. J., Olafson, K., ... & Anderson, D. G. (2019). Long-term implant fibrosis prevention in rodents and non-human primates using crystallized drug formulations. *Nature Materials*, 18(8), 892-904.

204. Veiseh, O., *et al*. (2015). Size- and shape-dependent foreign body immune response to materials implanted in rodents and non-human primates. *Nature Materials*, 14(6), 643-651.

205. Sussman, E. M., Halpin, M. C., Muster, J., Moon, R. T., & Ratner, B. D. (2014). Porous implants modulate healing and induce shifts in local macrophage polarization in the foreign body reaction. *Annals of Biomedical Engineering*, 42(7), 1508-1516.

206. Ward, W. K. (2008). A review of the foreign-body response to subcutaneously-implanted devices: the role of macrophages and cytokines in biofouling and fibrosis. *Journal of Diabetes Science and Technology*, 2(5), 768-777.

207. Klueh, U., Kreutzer, D. L., & Bryers, J. D. (2007). Biomaterial-mediated alterations of the foreign body response. *Journal of Biomedical Materials Research Part A*, 80(3), 752-766.

208. Morais, J. M., Papadimitrakopoulos, F., & Burgess, D. J. (2010). Biomaterials/tissue interactions: possible solutions to overcome foreign body response. *The AAPS Journal*, 12(2), 188-196.

209. Anderson, J. M., Rodriguez, A., & Chang, D. T. (2008). Foreign body reaction to biomaterials. *Seminars in Immunology*, 20(2), 86-100.

210. Bryers, J. D., Giachelli, C. M., & Ratner, B. D. (2012). Engineering biomaterials to integrate and heal: the biocompatibility paradigm shifts. *Biotechnology and Bioengineering*, 109(8), 1898-1911.

211. Onuki, Y., Bhardwaj, U., Papadimitrakopoulos, F., & Burgess, D. J. (2008). A review of the biocompatibility of implantable devices: current challenges to overcome foreign body response. *Journal of Diabetes Science and Technology*, 2(6), 1003-1015.

212. Norton, L. W., & Tegnell, E. (2005). *In vitro* and *in vivo* characterization of expanded polytetrafluoroethylene–poly lactic acid-co-glycolic acid scaffolds for vascular tissue engineering. *Biomaterials*, 26(17), 3485-3493.

213. Zhang, L., Cao, Z., Bai, T., Carr, L., Ella-Menye, J. R., Irvin, C., ... & Jiang, S. (2013). Zwitterionic hydrogels implanted in mice resist the foreign-body reaction. *Nature Biotechnology*, 31(6), 553-556.

214. Dang, T. T., Bratlie, K. M., Bogatyrev, S. R., Chen, X. Y., Langer, R., & Anderson, D. G. (2011). Spatiotemporal effects of a controlled-release anti-inflammatory drug on the cellular dynamics of host response. *Biomaterials*, 32(19), 4464-4470.

215. Voskerician, G., Shive, M. S., Shawgo, R. S., von Recum, H., Anderson, J. M., Cima, M. J., & Langer, R. (2003). Biocompatibility and biofouling of MEMS drug delivery devices. *Biomaterials*, 24(11), 1959-1967.

216. Grist, S. M., *et al*. (2019). Laser-inscribed graphene electrodes for aptamer-based biosensing. *ACS Sensors*, 4(12), 3298-3307.

217. Kassegne, S., *et al*. (2014). Electrical impedance spectroscopy of microelectrode arrays for cellular biosensing and drug screening. *Electroanalysis*, 26(6), 1161-1171.

218. Ingebrandt, S., & Offenhäusser, A. (2006). Label-free detection of DNA using field-effect transistors. *Physica Status Solidi (a)*, 203(14), 3399-3411.

219. Poghossian, A., & Schöning, M. J. (2014). Label-free sensing of biomolecules with field-effect devices for clinical applications. *Electroanalysis*, 26(6), 1197-1213.

220. Schöning, M. J., & Poghossian, A. (2002). Recent advances in biologically sensitive field-effect transistors (biofets). *Analyst*, 127(9), 1137-1151.

221. Murphy, S. V., & Atala, A. (2014). 3D bioprinting of tissues and organs. *Nature Biotechnology*, 32(8), 773-785.

222. Vijayavenkataraman, S., Yan, W. C., Lu, W. F., Wang, C. H., & Fuh, J. Y. H. (2018). 3D bioprinting of tissues and organs for regenerative medicine. *Advanced Drug Delivery Reviews*, 132, 296-332.

223. Groll, J., *et al*. (2018). Biofabrication: reappraising the definition of an evolving field. *Biofabrication*, 11(1), 013001.

224. Mandrycky, C., Wang, Z., Kim, K., & Kim, D. H. (2016). 3D bioprinting for engineering complex tissues. *Biotechnology Advances*, 34(4), 422-434.

225. Derakhshanfar, S., Mbeleck, R., Xu, K., Zhang, X., Zhong, W., & Xing, M. (2018). 3D bioprinting for biomedical devices and tissue engineering: A review of recent trends and advances. *Bioactive Materials*, 3(2), 144-156.

226. Ozbolat, I. T., & Hospodiuk, M. (2016). Current advances and future perspectives in extrusion-based bioprinting. *Biomaterials*, 76, 321-343.

227. Li, J., Chen, M., Fan, X., & Zhou, H. (2016). Recent advances in bioprinting techniques: approaches, applications and future prospects. *Journal of Translational Medicine*, 14(1), 271.

228. Zhang, Y. S., *et al*. (2017). 3D bioprinting for tissue and organ fabrication. *Annals of Biomedical Engineering*, 45(1), 148-163.

229. Gao, G., & Cui, X. (2016). Three-dimensional bioprinting in tissue engineering and regenerative medicine. *Biotechnology Letters*, 38(2), 203-211.

230. Hölzl, K., Lin, S., Tytgat, L., Van Vlierberghe, S., Gu, L., & Ovsianikov, A. (2016). Bioink properties before, during and after 3D bioprinting. *Biofabrication*, 8(3), 032002.

231. Knowlton, S., Onal, S., Yu, C. H., Zhao, J. J., & Tasoglu, S. (2015). Bioprinting for cancer research. *Trends in Biotechnology*, 33(9), 504-513.

232. Langer, R., & Vacanti, J. P. (2016). Advances in tissue engineering. *Journal of Pediatric Surgery*, 51(1), 8-12.

233. Seol, Y. J., Kang, H. W., Lee, S. J., Atala, A., & Yoo, J. J. (2014). Bioprinting technology and its applications. *European Journal of Cardio-Thoracic Surgery*, 46(3), 342-348.

234. Skardal, A., & Atala, A. (2015). Biomaterials for integration with 3-D bioprinting. *Annals of Biomedical Engineering*, 43(3), 730-746.

235. Ventola, C. L. (2015). Medical applications for 3D printing: current and projected uses. *Pharmacy and Therapeutics*, 40(10), 704.

236. Wang, X., *et al*. (2017). 3D printing of polymer matrix composites: A review and prospective. *Composites Part B: Engineering*, 110, 442-458.

237. Wei, L., & Li, K. (2018). 3D printing in medicine: technology overview and drug delivery applications. *Current Pharmaceutical Design*, 24(42), 5049-5061.

238. Xu, T., Zhao, W., Zhu, J. M., Albanna, M. Z., Yoo, J. J., & Atala, A. (2013). Complex heterogeneous tissue constructs containing multiple cell types prepared by inkjet printing technology. *Biomaterials*, 34(1), 130-139.

239. Zhang, Y. S., *et al*. (2016). Bioprinting 3D microfibrous scaffolds for engineering endothelialized myocardium and heart-on-a-chip. *Biomaterials*, 110, 45-59.

240. Zhu, W., Ma, X., Gou, M., Mei, D., Zhang, K., & Chen, S. (2016). 3D printing of functional biomaterials for tissue engineering. *Current Opinion in Biotechnology*, 40, 103-112.

241. Cohen, I. G., Amarasingham, R., Shah, A., Xie, B., & Lo, B. (2014). The legal and ethical concerns that arise from using complex predictive analytics in health care. *Health Affairs*, 33(7), 1139-1147.

242. Price, W. N. (2017). Artificial intelligence in health care: applications and legal implications. *The scitech Lawyer*, 14(1), 10-13.

243. Gerke, S., Minssen, T., & Cohen, G. (2020). Ethical and legal challenges of artificial intelligence-driven healthcare. *Artificial Intelligence in Healthcare*, 295-336.

244. Fogel, A. L., & Kvedar, J. C. (2018). Artificial intelligence powers digital medicine. *NPJ Digital Medicine*, 1(1), 1-4.

245. Matheny, M., Israni, S. T., Ahmed, M., & Whicher, D. (Eds.). (2019). *Artificial intelligence in health care: The hope, the hype, the promise, the peril*. National Academy of Medicine.

246. FDA. (2021). *Artificial Intelligence/Machine Learning (AI/ML)-Based Software as a Medical Device (samd) Action Plan*. U.S. Food and Drug Administration.

247. EMA. (2020). *Guideline on qualification and classification of stand-alone software used in healthcare within the regulatory framework of medical devices*. European Medicines Agency.

248. Parikh, R. B., Teeple, S., & Navathe, A. S. (2019). Addressing bias in artificial intelligence in health care. *JAMA*, 322(24), 2377-2378.

249. Obermeyer, Z., Powers, B., Vogeli, C., & Mullainathan, S. (2019). Dissecting racial bias in an algorithm used to manage the health of populations. *Science*, 366(6464), 447-453.

250. Char, D. S., Shah, N. H., & Magnus, D. (2018). Implementing machine learning in health care—addressing ethical challenges. *New England Journal of Medicine*, 378(11), 981-983.

251. Mittelstadt, B. D., Allo, P., Taddeo, M., Wachter, S., & Floridi, L. (2016). The ethics of algorithms: Mapping the debate. *Big Data & Society*, 3(2), 2053951716679679.

252. Wachter, S., Mittelstadt, B., & Floridi, L. (2017). Transparent, explainable, and accountable AI for robotics. *Science Robotics*, 2(6), eaan6080.

253. Amann, J., Blasimme, A., Vayena, E., Frey, D., & Madai, V. I. (2020). Explainability for artificial intelligence in healthcare: A multidisciplinary perspective. *BMC Medical Informatics and Decision Making*, 20(1), 1-9.

254. Goodman, K. W. (2016). *Ethics, medicine, and information technology: intelligent machines and the transformation of health care*. Cambridge University Press.

255. Vayena, E., & Blasimme, A. (2018). Health research with big data: Time for systemic oversight. *The Journal of Law, Medicine & Ethics*, 46(1), 119-129.

256. Ploug, T., & Holm, S. (2020). The four dimensions of contestable AI diagnostics–A patient-centric approach to explainable AI. *Artificial Intelligence in Medicine*, 107, 101901.

257. Leslie, D. (2019). Understanding artificial intelligence ethics and safety: A guide for the responsible design and implementation of AI systems in the public sector. *Arxiv preprint arxiv:1906.05684*.

258. Floridi, L., *et al*. (2018). AI4People—An ethical framework for a good AI society: opportunities, risks, principles, and recommendations. *Minds and Machines*, 28(4), 689-707.

259. Jobin, A., Ienca, M., & Vayena, E. (2019). The global landscape of AI ethics guidelines. *Nature Machine Intelligence*, 1(9), 389-399.

260. Hagendorff, T. (2020). The ethics of AI ethics: An evaluation of guidelines. *Minds and Machines*, 30(1), 99-120.

261. Rogers, J. A., Someya, T., & Huang, Y. (2010). Materials and mechanics for stretchable electronics. *Science*, 327(5973), 1603-1607.

262. Someya, T., Bao, Z., & Malliaras, G. G. (2016). The rise of plastic bioelectronics. *Nature*, 540(7633), 379-385.

263. Feiner, R., & Dvir, T. (2020). Tissue–electronics interfaces: from implantable devices to engineered tissues. *Nature Reviews Materials*, 5(9), 1-16.

264. Choi, S., Lee, H., Ghaffari, R., Hyeon, T., & Kim, D. H. (2016). Recent advances in flexible and stretchable bio-electronic devices integrated with nanomaterials. *Advanced Materials*, 28(22), 4203-4218.

265. Kim, D. H., *et al*. (2011). Epidermal electronics. *Science*, 333(6044), 838-843.

266. Ray, T. R., *et al*. (2019). Bio-Integrated wearable systems: A comprehensive review. *Chemical Reviews*, 119(8), 5461-5533.

267. Heikenfeld, J., *et al*. (2018). Accessing analytes in biofluids for peripheral biochemical monitoring. *Nature Biotechnology*, 37(5), 407-419.

268. Yetisen, A. K., Martinez-Hurtado, J. L., Ünal, B., Khademhosseini, A., & Butt, H. (2018). Wearables in medicine. *Advanced Materials*, 30(33), 1706910.

269. Bandodkar, A. J., & Wang, J. (2014). Non-invasive wearable electrochemical sensors: A review. *Trends in Biotechnology*, 32(7), 363-371.

270. Yang, Y., & Gao, W. (2019). Wearable and flexible electronics for continuous molecular monitoring. *Chemical Society Reviews*, 48(6), 1465-1491.

271. Guk, K., *et al*. (2019). Evolution of wearable devices with real-time disease monitoring for personalized healthcare. *Nanomaterials*, 9(6), 813.

272. Dunn, J., Runge, R., & Snyder, M. (2018). Wearables and the medical revolution. *Personalized Medicine*, 15(5), 429-448.

273. Piwek, L., Ellis, D. A., Andrews, S., & Joinson, A. (2016). The rise of consumer health wearables: promises and barriers. *PLOS Medicine*, 13(2), e1001953.

274. Pantelopoulos, A., & Bourbakis, N. G. (2010). A survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 40(1), 1-12.

275. Patel, S., Park, H., Bonato, P., Chan, L., & Rodgers, M. (2012). A review of wearable sensors and systems with application in rehabilitation. *Journal of neuroengineering and Rehabilitation*, 9(1), 21.

276. Chan, M., Estève, D., Fourniols, J. Y., Escriba, C., & Campo, E. (2012). Smart wearable systems: Current status and future challenges. *Artificial Intelligence in Medicine*, 56(3), 137-156.

277. Bonato, P. (2010). Wearable sensors and systems. *IEEE Engineering in Medicine and Biology Magazine*, 29(3), 25-36.

278. Appelboom, G., *et al*. (2014). Smart wearable body sensors for patient self-assessment and monitoring. *Archives of Public Health*, 72(1), 28.

279. Majumder, S., Mondal, T., & Deen, M. J. (2017). Wearable sensors for remote health monitoring. *Sensors*, 17(6), 130.

280. Ometov, A., *et al*. (2021). A survey on wearable technology: History, state-of-the-art, and current challenges. *Computer Networks*, 193, 108074.

281. Banaee, H., Ahmed, M. U., & Loutfi, A. (2013). Data mining for wearable sensors in health monitoring systems: A review of recent trends and challenges. *Sensors*, 13(12), 17472-17500.

282. Haghi, M., Thurow, K., & Stoll, R. (2017). Wearable devices in medical internet of things: scientific research and commercially available devices. *Healthcare Informatics Research*, 23(1), 4-15.

283. Silva, B. M., Rodrigues, J. J., de la Torre Díez, I., López-Coronado, M., & Saleem, K. (2015). Mobile-health: A review of current state in 2015. *Journal of Biomedical Informatics*, 56, 265-272.

284. Vashist, S. K., *et al*. (2015). Commercial smartphone-based devices and smart applications for personalized healthcare monitoring and management. *Diagnostics*, 5(3), 280-304.

285. Steinhubl, S. R., Muse, E. D., & Topol, E. J. (2015). The emerging field of mobile health. *Science Translational Medicine*, 7(283), 283rv3.

286. Kvedar, J. C., Fogel, A. L., Elenko, E., & Zohar, D. (2016). Digital medicine's march on chronic disease. *Nature Biotechnology*, 34(3), 239-246.

287. Firth, J., *et al*. (2017). The efficacy of smartphone-based mental health interventions for depressive symptoms: a meta-analysis of randomized controlled trials. *World Psychiatry*, 16(3), 287-298.

288. Lu, L., Zhang, J., Xie, Y., Gao, F., Xu, S., Wu, X., & Ye, Z. (2020). Wearable health devices in health care: Narrative systematic review. *JMIR mhealth and uhealth*, 8(11), e18907.

289. Kekade, S., Hseieh, C. H., Islam, M. M., Atique, S., Khalfan, A. M., Li, Y. C., & Abdul, S. S. (2018). The usefulness and actual use of wearable devices among the elderly population. *Computer Methods and Programs in Biomedicine*, 153, 137-159.

290. Pevnick, J. M., *et al*. (2018). Adoption of wearable devices by the consumer: a survey of the literature. *JMIR mhealth and uhealth*, 6(12), e112.

291. Sim, I. (2019). Mobile devices and health. *New England Journal of Medicine*, 381(10), 956-968.

292. Wright, R., *et al*. (2018). The impact of wearable sensors in healthcare on patient outcomes: a systematic review. *Journal of Medical Systems*, 42(11), 222.

293. Farias, F. A. C., *et al*. (2021). Wearable devices for physical activity and healthcare monitoring in elderly people: A critical review. *Clinics*, 76, e2331.

294. Ellenbogen, K. A., & Wilkoff, B. L. (2016). *Clinical cardiac pacing, defibrillation and resynchronization therapy* (5th ed.). Elsevier.

295. Grill, W. M., *et al*. (2009). Deep brain stimulation. *Annual Review of Biomedical Engineering*, 11, 601-628.

296. Farra, R., *et al*. (2012). First-in-human testing of a wirelessly controlled drug delivery microchip. *Science Translational Medicine*, 4(122), 122ra21.

297. Bouton, C. E. (2018). Restoring movement in paralysis with a bioelectronic neural bypass approach: Recent developments and future directions. *Cold Spring Harbor Perspectives in Medicine*, 8(11), a033969.

298. Proctor, C. M., & Slezia, A. (2021). Electrophysiology of the human brain–machine interface. *Science*, 372(6539), eabg1747.

299. Benabid, A. L., *et al*. (2019). Deep brain stimulation of the subthalamic nucleus for the treatment of Parkinson's disease. *The Lancet Neurology*, 18(7), 682-683.

300. Kipke, D. R., *et al*. (2008). Advanced neurotechnologies for chronic neural interfaces: New horizons and clinical opportunities. *Journal of Neuroscience*, 28(46), 11830-11838.