INTRODUCTION

Percutaneous coronary intervention with the aid of cardiovascular stents is the widely used therapeutic procedure for treating occlusive vascular diseases associated with the plaque deposition inside blood vessels. In spite of the momentous evolution and innovations in the field of medical technologies as well as biomaterial science, cardiovascular stents are still associated with several limitations. The introduction of bare metal stents, which revolutionized the field of interventional cardiology, was later hampered by the occurrence of restenosis (recurrence of arterial narrowing after surgery) and target lesion revascularization (repeated percutaneous intervention or revascularization within a stent) (Nordrehaug, Wiseth, & Bønaa, 2016; Piccolo et al., 2019). Repeated attempts to correct stenotic regions can often result in rupture of vessel that can elicit blood clot formation (thrombosis) or even lead to life-threatening haemorrhage (Farooq and Gogas Bill, 2011). Restenosis occurrence originating from proliferative neointimal tissue growth in response to strut-related injury and inflammation can be clinically evident typically within 6–9 months after stent placement (Alfonso, Byrne, Rivero, & Kastrati, 2014; Moliterno, 2005). In order to specifically address the restenosis problem, the first-generation drug-eluting stents with a drug-loaded (paclitaxel) polymer coating on a metallic platform (316L stainless steel) were developed (Kafkas & Dragasis, 2018; Katsanos, Spiliopoulos, Kitrou, Krokidis, & Karnabatidis, 2018; Torii et al., 2020). Joner et al.
reported this delayed arterial healing with drug-eluting stents as part of a study to investigate the long-term effects of stents on coronary arterial healing. The current standard of care in revascularization, the second-generation drug-eluting stent was introduced with ultrathin struts (80–90 µm), reduced drug loading and more biocompatible or biodegradable polymers (Bangalore, Toklu, Patel, Feit, & Stone, 2018; Beijk & Piek, 2007; Iannaccone et al., 2019; Palmerini et al., 2013). Nevertheless, the presence of antiproliferative drug and polymers can adversely elicit delayed or incomplete endothelialization obviating the need for a prolonged dual antiplatelet therapy (DAPT) (Bønaa et al., 2016; McFadyen, Schaff, & Peter, 2018). The most recent and promising stent technology is the bioabsorbable stents, which will undergo complete dissolution in physiological environment after performing transient vessel scaffolding. However, inferior clinical and angiographic outcomes reported during famous clinical trials (e.g. ABSORB trial) call into question the long-term superiority of these stents (Serruys et al., 2016). Moreover, the unmet dual requirements of optimal mechanical support and degradation kinetics in the physiological environment for the intended stenting period hinder the widespread clinical utilization of bioabsorbable stents (Fu et al., 2020; Hernández-Escobar et al., 2019). Figure 1 schematically illustrates the stent-related complications such as stent thrombosis, in-stent restenosis and neointimal hyperplasia (due to delayed endothelialization). Hence, it is highly imperative to develop a technology capable of eliminating these drawbacks in order to improve clinical efficiency as well as reducing the incidence of revascularization procedures.

In view of the global burden in terms of mortality and morbidity associated with this disease (Kaptoge et al., 2019; Roth et al., 2017), focus on potential technologies capable of providing prognostic information in case of an unlikely clinical event represents the need of the hour. Stents with an integrated sensing and communication based on micro-/nanoelectromechanical systems hold immense potential in providing diagnostic feedback to find a solution for early detection of any adverse thrombotic events. This technology can provide prognostic information, which is critical to enable timely interventions and reduce the chances for revascularization procedures. In the case of any unlikely clinical problem such as restenosis, thrombosis or delayed endothelialization, these sensing units can transmit signals wirelessly to a portable recording device. Following the nomenclature used by Takahata in his remarkable research contributions to this field, the term ‘smart stent’ is used throughout this article to represent stent systems with embedded sensors.

In spite of all the research, the clinical translation of a smart stent with integrated sensor technology is yet to be achieved. Vast majority of recent reviews are focused on the bioresorbable stent materials, drug-eluting stents and bioresorbable electronics (Bowen et al., 2016; Cha, Kang, Lee, & Kim, 2019; Jinnouchi et al., 2019; Mostaed, Sikora-Jasinska, Drelich, & Vedani, 2018). The present minireview highlights the recent advancements in the field of the cardiovascular smart stent systems (both permanent and bioresorbable) with integrated sensors with focus on the existing challenges as well as potential future solutions. It is highly imperative to collate the recent research in the field of smart stents to provide a knowledge platform for enabling translational research in this field. In view of these perspectives, the smart stent systems to detect endothelialization and in-stent restenosis are discussed in the first two sections. Innovative bioabsorbable technologies are subsequently reviewed followed by an overview on the future perspectives.

2 SMART STENTS TO DETECT ENDOTHELIALIZATION

Prognostic relevance of endothelial coverage to check the incidence of late stent thrombosis is well established, and monitoring of endothelialization can assist in the early detection of stent thrombosis.

FIGURE 1 Schematic representation of the major limitations associated with cardiovascular stents. (a) Stent thrombosis occurs due to the blood clot formation inside stent region. (b) In-stent restenosis develops with the re-occurrence of fatty deposition (as shown in yellow) in the stenotic region. (c) After stent is implanted, delayed endothelialization or endothelial denudation leads to the migration of smooth muscle cells from the middle layer of blood vessel leading to smooth muscle cell proliferation and neointimal hyperplasia.
Musick, Coffey, and Irazoqui (2010) developed a self-actuating, self-sensing piezoelectric sensor based on a plasma-treated hydrophilic parylene-coated micro-cantilever. When endothelial cells come in contact with the sensors attached on the stent surface, the effective mass and surface charge will vary, thereby altering the resonance frequency of the micro-cantilever providing information regarding stent endothelialization. Even though, it should be pinpointed that for a stent in a physiological environment undergoing normal healing or restenosis, a dense thicker layer comprising of distinctive cell variants can limit this cantilever vibration resulting in undetectable resonant frequencies. The future research can focus on discerning the distinctive cell types with high sensitivity. With the development of nanoelectromechanical systems (NEMS) such as nanomechanical resonators (Munawar et al., 2019; Ye, Lee, & Feng, 2017), mass analysis in the range of mega- to gigadalton range including that of most viruses and disease biomarkers is possible (Dominguez-Medina et al., 2018; Gil-Santos et al., 2010). In nanoscale, the response of such nanoresonators depends not only on the mass of the adsorbed cells but also on the mechanical properties of those cells (Ramos, Tamayo, Mertens, Calleja, & Zaballos, 2006). Another promising concept garnering research interest is the detection of molecular markers such as nitrous oxide (NO). Since NO is gaseous signalling molecule indicating re-endothelialization (Bedair, ElNaggar, Joung, & Han, 2017; Li et al., 2018), detection of insufficient NO generation can be a potential sensing strategy. Recently developed optofluidic sensor with a nanofilter comprising of an array of nanowells to detect haemolysis by separating haemoglobin (Zhou et al., 2018) and 3D nanoplasmonic biosensor to detect cell filopodia (Zhu, Eldeeb, & Pang, 2020) represents prospective approaches in this direction (Figure 2(a,b)).

3 | SMART STENTS TO MONITOR RESTENOSIS

In-stent restenosis obstructs the normal blood flow inside blood vessels and will consequently result in variations of local blood pressure, haemodynamics and blood flow characteristics. The early signs of in-stent restenosis can be detected with the aid of a pressure sensor by proper monitoring of these parameters. Various types of

![Figure 2](image-url)
pressure sensors and their mechanisms for distinctive biomedical applications are recently reviewed (Han, Kundu, Nag, & Xu, 2019; Honjol et al., 2020). Chow, Ouyang, Beier, Chappell, and Irazoqui (2009) developed an active sensing stent to analyse the pulmonary arterial pressures both in vivo and by simulations for calculating tissue-induced power loss. However, the positioning of stent antenna with the aid of conductive rings on the outer surface of the stent can lead to complications during interventional procedures. Moreover, a Parylene C-based wireless sensor to analyse cardiovascular pressure demonstrated sufficient sensitivity (8.25 × 10⁻³/mmHg) and linearity (91.5% over the range of 0–50 mmHg), which needs to be assessed for in vivo performance and long-term biocompatibility (Yeh, Lo, Xu, & Yang, 2019). Apart from these, an ultrathin, flexible pressure sensor fabricated from poliyimide–carbon nanotube composite with a wide pressure sensing range (10–500 kPa) represents a pertinent system for catheter or stent applications (Jeong, Park, Lee, Kim, & Park, 2020).

Wireless, passive magnetoelastic sensors based on iron-based metallic glass ribbons when applied with an alternating magnetic field can determine mass loading or viscosity variations based on the resonant frequency variations (Ren, Yu, & Tan, 2019). Magnetoelastic sensors bonded to the interior walls of a strontium ferrite-coated Co-Cr alloy stents were used to evaluate intimal proliferation in vivo (Green, Kwon, Elta, & Gianchandani, 2010). Results demonstrated signal acquisition from distances of at least 5 cm and viscosity evaluation of biological fluids. Sensors were fabricated from a thin amorphous metallic glass ribbon of Metglas 2605SA1 (Fe (85–95%), Si (5–10%) and B (1–5%)) and were bonded to the coated stent using polydimethylsiloxane (PDMS). Even though PDMS is ubiquitously being utilized for microfluidic applications, a strong/permanent PDMS bonding to a metallic or polymeric surface is not always trivial owing to its inherent lower surface energy (Agostini, Greco, & Cecchini, 2019). Hence for stenting applications, which need tortuous blood vessel motions, compression and expansion, the bonding strength should be strong enough to withstand these external factors. Moreover, for stent applications, PDMS in contact with blood can initiate coagulation and thrombosis (Leung et al., 2015). Another unique iron-based magnetic material is galfenol (iron–gallium alloy), which has been reported for wireless stent material applications (DeRouin et al., 2019). For magnetoelastic biosensor applications, an iron–gallium alloy (Fe₈₃Ga₁₇) was developed for which the performance was dependent on the annealing treatment (Sang et al., 2014).

Pioneering research by Kenichi Takahata group has provided significant contributions in the field of pressure sensor-integrated telemetric stents. Takahata proposed the concept of utilizing the stent platform itself as a wireless link. A schematic illustration depicting the usage of the whole stent as antenna is shown in Figure 2c (Liu, Chen, & Hsiao, 2019). Upon local haemodynamic pressure variations, capacitive pressure sensor works as a variable capacitor and the stainless steel stent platform itself can act as the electrical inductor or antenna. Micron-sized stainless steel (304SS) structures were initially used to make inductive stent antenna integrated with silicon capacitive pressure sensors for intraluminal pressure and flow measurements (Takahata, Gianchandani, & Wise, 2006). The pressure sensors were bonded to stent platform using enamel, and the device was coated with Parylene C (0.5 μm thick) for electrical insulation. Even though this preliminary study demonstrated deployment compatibility during stenting as well as pressure/flow monitoring, the biocompatibility aspects of the structures in blood environment and drug-eluting ability were not evaluated. In the succeeding work, a novel capacitive pressure sensor chip fabricated from stainless steel (316LSS) was developed for which the in vivo studies revealed a frequency sensitivity of up to 146 ppm/mmHg over a pressure range of 250 mmHg (Chen, Brox, Assadsangabi, Hsiang, & Takahata, 2014). Compared to previous silicon-based sensors, these 316LSS sensors offer advantages such as a) ability to act as one of the capacitive electrodes, (b) elimination of additional electrical lead joints and (c) reliable mechanical joint by laser micro-welding. The 316L SS platforms were gold-electroplated, the radiofrequency pressure sensors were capped by a polyimide bonding of a metal–polymer composite, and finally, the whole smart stent system was Parylene-coated. This work highlighted the limitations associated with reduced sensing resolution and constrained device packaging (electrical failures occurred during animal studies). The first demonstration of a transient resonance method with an RF telemetric smart stent was later reported by the same group (Brox, Chen, Mirabbasi, & Takahata, 2016). Gold-coated 316L SS integrated with a MEMS capacitive pressure sensor of the same 316LSS material as discussed above revealed effective wireless read distances up to 2.75 cm, promising for carotid artery (arteries close to skin supplying blood to brain and head) applications. Laser micro-welding of capacitive pressure sensor onto a 316L stainless steel platform demonstrated permanent bonding with simultaneous mechanical and electrical performances as compared to conventional adhesive bonding approaches (Chen, Brox, Assadsangabi, Mohamed Ali, & Takahata, 2017). Recently, the same research group has developed a promising smart stent technology encompassing a balloon-expandable 316L SS and a MEMS sensor micro-welded together (Figure 2d) with high-performance sensing function (resolution of 12.4 mmHg) and mechanical robustness (Chen, Assadsangabi, Hsiang, & Takahata, 2018). Change in resonant frequency of MEMS sensor-stent combination gives an indication of the surrounding blood pressure, and it can be measured by creating an inductive coupling of this system with a handheld portable reader with an external antenna. The mechanical robustness of this smart stent system was successfully demonstrated by withstanding a crimping force of up to 100 N and balloon expansion pressure up to 16 atm, thanks to laser micro-welding for withstanding these forces. Apart from measuring absolute pressure or pressure differences, the variations in pulse wave velocity according to the increasing stiffness or narrowing of blood vessel can also be beneficial (Safar, 2018).

4 | BIOABSORBABLE SMART STENTS

Bioabsorbable stents offer innovative paradigms in the field of stent angioplasty capable of reducing the clinical complications associated
with the presence of a permanent implant material in the vascular lumen. Even though hailed as the future of coronary stenting, biodegradable stents have not yet attained the expected clinical efficacy. The rapid advancements in the field of biodegradable electronic materials (Cha et al., 2019; Chen & Ahn, 2020; Kang, Koo, Lee, & Rogers, 2018) can be incorporated to bioabsorbable stent systems to develop novel bioabsorbable smart stents. In spite of its biological advantage, bioresorbable electronic systems can mitigate the problems associated with ever-growing electronic waste posing hazardous environmental impacts (Ye et al., 2017). One of the challenges associated with bioresorbable sensors for clinical applications inside human body is the inability to sustain consistent sensing function in biofluids throughout the intended scaffolding period before undergoing complete resorption (Shin et al., 2019).

Biodegradable poly-L-lactide (PLLA)-based piezoelectric force sensors, which were developed for measuring bio-physiological pressures, exhibited precise measurements in a wide range of 0–18 kPa (Curry et al., 2018). A promising technology in this direction, a bioresorbable magnesium alloy electronic stent integrated with nanomembrane-based flexible flow/temperature sensors and drug-infused nanoparticles system, was first reported by Son et al. (2015) The conductive Mg-Zn-Mn alloy (ZM21; Mg 97%, Zn 2%, Mn 1%) was used as the antenna system for wireless telemetry, and the whole stent system was comprised of bioresorbable and bioinert materials. The nanoscale encapsulated coating on a poly (lactic acid) (PLA) film on stent surface included ceria (CeO2) nanoparticles for catalytic ROS scavenging and gold nanorod core/mesoporous silica nanoparticles shell to control drug-loading and photothermal therapy as shown in Figure 3a. This propitious work has opened new avenues in designing multifunctional electronic and therapeutic utilities such as data sensing, bioresorption, localized drug release and photothermal therapy incorporated in a single stent system.

A biodegradable polymer smart stent integrated with a wireless pressure sensor measured pressure in the range of 0-230 mmHg with a sensitivity of 0.043 MHz/mmHg (Park et al., 2016). The polymer stent was 3D printed from biodegradable polycaprolactone, and sensor was made of a photosensitive and biocompatible SU-8 polymer (Figure 3(b,c)). SU-8 polymer is biocompatible with stable electro-optical characteristics making it an attractive material for bioelectronics (Matarèse et al., 2018); however, it is not bioabsorbable. One year later, with further refinement of material technology, the same research group has developed a fully absorbable smart stent system based on poly(D-lactide) (PDLA) wireless pressure sensor and the same 3D printed polycaprolactone stent as shown in Figure 3(d-e) (Park, Kim, Park, & Lee, 2019). This system has demonstrated a high linearity in the pressure range of 0–120 mmHg and a sensitivity of 50 kHz/mmHg. Table 1 summarizes the research on the prominent material technologies used for developing smart stent systems. Well-established silicon technologies, advancements in the field of additive manufacturing and bioresorbable materials can lead to further advancements in the field of bioresorbable smart stent-sensor technology.

**FIGURE 3** (a) Schematic depiction of bioresorbable Mg alloy stent with temperature/flow sensors, memory modules and nanotherapeutic agents such as ceria nanoparticles and gold nanorod with mesoporous silica nanoparticles. Reprinted from Son et al. (2015), with permission from American Chemical Society. (b–c) 3D-printed polycaprolactone polymer stents embedded with SU-8 polymer-based wireless micro-pressure sensors and the smart stent system connected to external antenna to detect the sensor resonant frequency. Reprinted from Park et al. (2016), with permission from MDPI. (d–e) Biodegradable poly(D-lactide) pressure sensor embedded inside 3D-printed polycaprolactone. Reprinted from Park et al. (2019), with permission from Elsevier. (f) Co-Cr-based bare metal stent integrated with an L-C resonance pressure sensor. Reprinted from Park et al. (2016), with permission from MDPI.
| Stent material       | Sensor material               | Fabrication technique                          | Bonding agent                                   | Coating on sensor                                         | Ref.                                      |
|----------------------|-------------------------------|------------------------------------------------|------------------------------------------------|----------------------------------------------------------|-------------------------------------------|
| Polyethylene         | Two Metglas™ 2826 MB foils bonded together by gold-indium eutectic bonding. | Microelectrodischarge machining (µEDM)         | Threaded through holes on stents with polyethylene tethers | Coated with 100 nm Al₂O₃ layer by atomic layer deposition (ALD) | Jiang, Nambian, Green, and Gianchandani (2019) |
| Elgiloy              | Metglas™ 2605SA1               | Photochemical machining process                | Polydimethylsiloxane (PDMS)                      | Conformal magnetic layer of strontium ferrite (SrFe) particles | Green et al. (2010)                       |
| Polyethylene         | Metglas™ 2826 MB (Ni-Fe-Mo-B alloy) | Photochemical machining process                | Thermal staking method.                         | Parylene C coating (2 µm thick layer)                    | Green, Kwon, Elta, and Gianchandani (2013) |
| -                    | Si substrate (4 µm thick)      | Micromachined commercially available cantilevers | Liquid crystal polymer package                  | Parylene C using CVD (1.5 µm thick)                      | Musick et al. (2010)                     |
| 304 steel            | Silicon                       | Micromachining                                 | Enamel                                         | Parylene C (1.5 µm)                                      | Takahata et al. (2006)                    |
| 316L stainless steel with gold electroplating (15 µm thick) | Stainless steel chip capped by polyimide bonding of a polymer-metal composite membrane | Microelectrodischarge machining technique      | Conductive epoxy                                     | Parylene C coating (2–3 µm)               | Chen et al. (2014)                       |
| 316L stainless steel with gold coating | 316L stainless steel          | –                                               | –                                              | 2–3 µm of Parylene C                                     | Brox et al. (2016)                       |
| Electropolished 316 stainless steel | Stainless steel as the sensor’s substrate and as fixed capacitive electrode, and a gold-titanium-polyimide multilayered diaphragm serving as deformable electrode | Laser micro-welding using a Nd:YAG fibre laser with 1070 nm wavelength | Gold electroplated and insulated by conformal Parylene C coating, 20 µm | Chen et al. (2018)                        |
| Magnesium alloy (a Mg-Zn-Mn alloy (ZM21; Mg 97%, Zn 2%, Mn 1%)) | Flow/temperature sensors based on Mg, ZnO, MgO, PLA | Deposition via electron beam evaporation        | Solvent vapour-assisted transfer-printing, rolling and gluing | Coated with nanoscale therapeutic agents (ceria nanoparticles and gold nanorods@mesoporous silica nanoparticles) and drugs | Son et al. (2015)                       |
| Polycaprolactone (PCL) | Photosensitive SU-8 polymer | –                                               | –                                              | –                                                        | Park et al. (2016)                       |
| Polycaprolactone (PCL) | Poly(D-lactide) (PDLA) | Microelectromechanical system                   | –                                              | –                                                        | Park et al. (2019)                       |
CONCLUSIONS AND FUTURE PERSPECTIVES

Smart stents with integrated sensor systems are garnering substantial research interest in view of their potential to provide a real-time monitoring to mitigate the clinical problems associated with current cardiovascular stents. The materials used should be haemocompatible without eliciting adverse reactions. In spite of the fact that research advancements are being made on laboratory scale, several challenges pertaining to the clinical application of these stent systems have not yet been addressed. Firstly, secure encapsulation of the sensors to withstand the contact forces during the navigation through tortuous vasculature during the interventional procedure is a critical aspect. For attaining this, the whole sensor system should be stretchable and flexible without impeding the normal blood flow.

Extremely stretchable (500% radial stretching) and bendable (180° with 0.75 mm radius of curvature) nanostructured flow sensor developed for intra-aneurysm (Howe, Mishra, & Kim, 2018) as shown in Figure 4a (for detecting precise blood flow velocity variations) can also be promising for stent applications.

Since bioabsorbable stents are hailed as the future of coronary interventions, research focused on integrating electronic components which are bioabsorbable with controllable triggered degradation kinetics is of high significance. Biodegradable, flexible sensor developed by Boutry et al. demonstrated arterial pulse monitoring by a capacitive sensor capable of measuring vessel diameter changes with respect to time (Boutry et al., 2019). This sensor was comprised entirely of biodegradable materials and was based on fringe-field-capacitive sensing designed to work even with small diameter blood vessel pulse variations. Furthermore,
bioresorbable nanoporous silicon-based sensors for brain demonstrated real-time monitoring of dopamine secretion levels (Figure 4b) (Kim et al., 2018), intracranial pressure monitoring (Figure 4c) (Yang et al., 2020) and simultaneous pressure and temperature measurements (Kang et al., 2016). Apart from the precise measurement of pressure, temperature, motion, flow, thermal properties and pH, the sensors and their by-products exhibited biocompatible dissolution revealing their potentiality for a wide range of biomedical applications. In addition to these, an online monitoring strategy to sense the bioresorption rate inside physiological environment can bring about profound benefits (Shittu, Sadeghilaridjani, Pole, Ayyagari, & Mukherjee, 2020).

Apart from these factors, thin strutted stents are clinically proven to reduce in-stent restenosis. The famous ISAR-STEREO clinical trials demonstrated that risks associated with restenosis could be reduced up to 42% with the use of thin strutted stent (Kastrati et al., 2001; Pache et al., 2003). Hence, integrating the sensor components to fit inside newer-generation thin strutted stents should be taken care. Research can also take into account the relevance of radiopaque sensor materials which can be advantageous during interventional procedure and follow-up fluoroscopic techniques. Furthermore, innovative additive manufacturing systems offer new avenues for improving the high-throughput and large-scale manufacturing opportunities (Guerra & Ciurana, 2018; Herbert, Mishra, Lim, Yoo, & Yeo, 2019; Wen et al., 2018). Most importantly, the emerging field of Internet of Things (IoT), a new paradigm in patient health care, can improve clinical outcomes by utilizing data techniques for patients’ future health predictions (Dimitrov, 2016; Hoare, Bussooa, Neale, Mirzai, & Mercer, 2019).

In summary, smart stents with embedded sensors can revolutionize the field of interventional cardiology with collaborative research by the integration of cardiovascular biology, engineering, biomaterial science and nanotechnology.

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CONFLICT OF INTEREST

There are no conflicts of interest to declare.

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REFERENCES

Agostini, M., Greco, G., & Cecchini, M. (2019). Polydimethylsiloxane (PDMS) irreversible bonding to untreated plastics and metals for microfluidics applications. APL Materials, 7(8), 081108.
Alfonso, F., Byrne, R. A., Rivero, F., & Kastrati, A. (2014). Current treatment of in-stent restenosis. Journal of the American College of Cardiology, 63(24), 2659–2673.
Bangalore, S., Toklu, B., Patel, N., Feit, F., & Stone, G. W. (2018). Newer-generation ultrathin strut drug-eluting stents versus older second-generation thicker strut drug-eluting stents for coronary artery disease. Circulation, 138(20), 2216–2226.
Bedair, T. M., ElNaggar, M. A., Joung, Y. K., & Han, D. K. (2017). Recent advances to accelerate re-endothelialization for vascular stents. Journal of Tissue Engineering, 8, 2041731417731546.
Beijk, M. A. M., & Piek, J. J. (2007). XIENCE V everolimus-eluting coronary stent system: A novel second generation drug-eluting stent. Expert Review of Medical Devices, 4(1), 11–21.
Banæa, K. H., Mannsverk, J., Wiseth, R., Aaberge, L., Myreng, Y., Nygård, O., ... Nordrehaug, J. E. (2016). Drug-eluting or bare-metal stents for coronary artery disease. New England Journal of Medicine, 375(13), 1242–1252.
Boutruy, C. M., Becker, L., Kaizawa, Y., Vassos, C., Tran, H., Hinckley, A. C., ... Bao, Z. (2019). Biodegradable and flexible arterial-pulse sensor for the wireless monitoring of blood flow. Nature Biomedical Engineering, 3(1), 47–57.
Bowen, P. K., Shearier, E. R., Zhao, S., Guillory, R. J., Zhao, F., Goldman, J., & Drelich, J. W. (2016). Biodegradable metals for cardiovascular stents: From clinical concerns to recent zn-alloys. Advanced Healthcare Materials, 5(10), 1121–1140.
Brox, D. S., Chen, X., Mirabbasi, S., & Takahata, K. (2016). Wireless telemetry of stainless-steel-based smart antenna stent using a transient resonance method. IEEE Antennas and Wireless Propagation Letters, 15, 754–757.
Cha, G. D., Kang, D., Lee, J., & Kim, D.-H. (2019). Bioreosorbable electronic implants: History, materials, fabrication, devices, and clinical applications. Advanced Healthcare Materials, 8(11), 1801660.
Chen, X., & Ahn, J.-H. (2020). Biodegradable and bioabsorbable sensors based on two-dimensional materials. Journal of Materials Chemistry B, 8(6), 1082–1092.
Chen, X., Assadsangabi, B., Hsiang, Y., & Takahata, K. (2018). Enabling angioplasty-ready “Smart” stents to detect in-stent restenosis and occlusion. Advanced Science, 5(5), 1700560.
Chen, X., Brox, D., Assadsangabi, B., Hsiang, Y., & Takahata, K. (2014). Intelligent telemetric stent for wireless monitoring of intravascular pressure and its in vivo testing. Biomedical Microdevices, 16(5), 745–759.
Chen, X., Brox, D., Assadsangabi, B., Mohamed Ali, M. S., & Takahata, K. (2017). A stainless-steel-based implantable pressure sensor chip and its integration by microwelding. Sensors and Actuators A: Physical, 257, 134–144.
Chow, E. Y., Ouyang, Y., Beier, B., Chappell, W. J., & Irazoqui, P. P. (2009). Evaluation of cardiovascular stents as antennas for implantable wireless applications. IEEE Transactions on Microwave Theory and Techniques, 57(10), 2523–2532.
Curry, E. J., Ke, K., Chorsi, M. T., Wrobel, K. S., Miller, A. N., Patel, A., ... Nguyen, T. D. (2018). Biodegradable piezoelectric force sensor. Proceedings of the National Academy of Sciences, 115(5), 909–914.
DeRouin, A., Guillory, R., He, W., Frost, M., Goldman, J., & Ong, K. G. (2019). Magnetoelastic galfenol as a stent material for wirelessly controlled degradation rates. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 107(2), 232–241.
Dimitrov, D. V. (2016). Medical internet of things and big data in healthcare. Healthcare Informatics Research, 22(3), 156–163.
Dominguez-Medina, S., Fostner, S., Defoort, M., Sansa, M., Stark, A.-K., Halim, M. A., ... Hetz, S. (2018). Neutral mass spectrometry of virus capsids above 100 megadaltons with nanomechanical resonators. Science, 362(6417), 918.
Farooq, V., & Gogas Bill, D. (2011). Serruys Patrick W. Restenosis. Circulation: Cardiovascular Interventions, 4(2), 195–205.
Fu, J., Su, Y., Qin, Y.-X., Zheng, Y., Wang, Y., & Zhu, D. (2020). Evolution of metallic cardiovascular stent materials: A comparative study among stainless steel, magnesium and zinc. Biomaterials, 230, 119641.
Gil-Santos, E., Ramos, D., Martínez, J., Fernández-Regúlez, M., García, R., San Paulo, Á., … Tamayo, J. (2010). Nanomechanical mass sensing and stiffness spectrometry based on two-dimensional vibrations of resonant nanowires. Nature Nanotechnology, 5(9), 641–645.

Green, S. R., Kwon, R. S., Elta, G. H., & Gianchandani, Y. B. (2010). In situ and ex vivo evaluation of a wireless magnetoelectric biliary stent monitoring system. Biomedical Microdevices, 12(3), 477–484.

Green, S. R., Kwon, R. S., Elta, G. H., & Gianchandani, Y. B. (2013). In vivo and in situ evaluation of a wireless magnetoelectric sensor array for plastic biliary stent monitoring. Biomedical Microdevices, 15(3), 509–517.

Guerra, A. J., & Ciurana, J. D. (2018). Three-dimensional tubular printing of bioabsorbable stents: The effects process parameters have on in vitro degradation. 3D Printing and Additive Manufacturing, 6(1), 50–56.

Han, T., Kundu, S., Nag, A., & Xu, Y. (2019). 3D printed sensors for biomedical applications: A review. Sensors, 19(7), 1706.

Herbert, R., Mishra, S., Lim, H.-R., Yoo, H., & Yeo, W.-H. (2019). Fully implantable, wireless, stretchable implantable Biosystem toward Batteryless, real-time monitoring of cerebral aneurysm hemodynamics. Advanced Science, 6(18), 1901034.

Hernández-Escobar, D., Champagne, S., Yilmazer, H., Dikici, B., Boehlert, C. J., & Hermawan, H. (2019). Current status and perspectives of zinc-based absorbable alloys for biomedical applications. Acta Biomaterialia, 97, 1–22.

Hoare, D., Busssooa, A., Neale, S., Mirzaiz, N., & Mercer, J. (2019). The future of cardiovascular stents: Bioresorbable and integrated biosensor technology. Advanced Science, 6(20), 1900856.

Honjol, Y., Rajkumar, V., S., Parent-Harvey, C., Selvasanand, K., Kordlouie, S., Comeau-Gauthier, M., … Merle, G. (2020). Current view and prospect: Implantable pressure sensors for health and surgical care. Medical Devices & Sensors, 3(3), e10068.

Howe, C., Mishra, S., Kim, Y.-S. et al. (2018). Stretchable, implantable, nanostuctured flow-diverter system for quantification of intra-aneurysmal hemodynamics. ACS Nano, 12(8), 8706–8716.

Iannaccone, M., Gatti, P., Barbero, U., Bassignana, A., Gallo, D., Benedictis, M., … D’Ascenzo, F. (2019). Impact of strut thickness and number of crown and connectors on clinical outcomes on patients treated with second-generation drug eluting stent. Catheterization and Cardiovascular Interventions. http://dx.doi.org/10.1002/ccd.28228

Jeong, Y., Park, J., Lee, J., Kim, K., & Park, I. (2020). Ultrathin, biocompatible, and flexible pressure sensor with a wide pressure range and its biomedical application. ACS Sensors, 5(2), 481–489.

Jiang, J., Nambisan, R. M., Green, S. R., & Gianchandani, Y. B. (2019). Encapsulation approaches for in-stent wireless magnetoelectric sensors. IEEE Transactions on Biomedical Engineering, 66(7), 2044–2052.

Jinnouchi, H., Torii, S., Sakamoto, A., Kolodgie, F. D., Virmani, R., & Finn, A. V. (2019). Fully biodegradable vascular scaffolds: Lessons learned and future directions. Nature Reviews Cardiology, 16(5), 286–304.

Joner, M., Finn, A. V., Farb, A., Mont, E. K., Kolodgie, F. D., Ladich, E., … Virmani, R. (2006). Pathology of strut thickness effect on restenosis outcome (ISAR-STEREO-2) trial. Journal of the American College of Cardiology, 48(1), 193–202.

Kafka, N., & Dragasis, S. (2018). Current knowledge on very late stent thrombosis. Continuing Cardiology Education, 4(1), 40–44.

Kang, S.-K., Koo, J., Lee, Y. K., & Rogers, J. A. (2018). Advanced materials and devices for bioregradable electronics. Accounts of Chemical Research, 51(5), 988–998.

Kang, S.-K., Murphy, R. K. J., Hwang, S.-W., Lee, S. M., Harburg, D. V., Krueger, N. A., … Rogers, J. A. (2016). Biodegradable silicon electronic sensors for the brain. Nature, 530(7588), 71–76.

Kapteg, S., Pennells, L., De Bacquer, D., Cooney, M. T., Kavousi, M., Stevens, G., … Amouyel, P. (2019). World Health Organization cardiovascular disease risk charts: revised models to estimate risk in 21 global regions. The Lancet Global Health, 7(10), e1332–e1345.

Kastrati, A., Mehilli, J., Dirschinger, J., Dotzer, F., Schuhlen, H., Neumann, F.-J., … Schöming, A. (2001). Intracoronary stenting and angiographic results. Circulation, 103(23), 2816–2821.

Katsanos, K., Spiroliopoulos, S., Kitrou, P., Krokidis, M., & Karnabatidis, D. (2018). Risk of death following application of paclitaxel-coated balloons and stents in the femoropopliteal artery of the leg: A systematic review and meta-analysis of randomized controlled trials. Journal of the American Heart Association, 7(24), e011245.

Khan, W., Farah, S., & Domb, A. J. (2012). Drug eluting stents: Developments and current status. Journal of Controlled Release, 161(2), 703–712.

Kim, H.-S., Yang, S. M., Jang, T.-M., Oh, N., Kim, H.-S., & Hwang, S.-W. (2018). Bioreabsorable silicon nanomembranes and iron catalyst nanoparticles for flexible, transient electrochemical dopamine monitors. Advanced Healthcare Materials, 7(24), 1801071.

Leung, J. M., Berry, L. R., Atkinson, H. M., Cornelius, R. M., Sandejas, D., Rochow, N., … Brash, J. L. (2015). Surface modification of poly(dimethylsiloxane) with a covalent antithrombin–heparin complex for the prevention of thrombosis: Use of polydopamine as bonding agent. Journal of Materials Chemistry B, 3(29), 6032–6036.

Li, X., Shen, F., Wang, K., Lin, S., Zhou, L., Chen, S., … Huang, N. (2018). Endothelial mimetic multifunctional surfaces fabricated via poly-dopamine mediated copper immobilization. Journal of Materials Chemistry B, 6(46), 7582–7593.

Liu, C.-H., Chen, S.-C., & Hsiao, H.-M. (2019). A single-conector stent antenna for intravascular monitoring applications. Sensors, 19(21), 4616.

Matarése, B. F. E., Feyen, P. L. C., Falco, A., Benfenati, F., Lugli, P., & de Mello, J. C. (2018). Use of SU8 as a stable and biocompatible adhesion layer for gold bioelectrodes. Scientific Reports, 8(1), 5560.

McFadyen, J. D., Schaff, M., & Peter, K. (2018). Current and future antiplatelet therapies: Emphasis on preserving haemostasis. Nature Reviews Cardiology, 15(3), 181–191.

Moliterno, D. J. (2005). Healing Achilles — Sirolimus versus Paclitaxel. New England Journal of Medicine, 353(7), 724–727.

Mostaed, E., Sikora-Jasinska, M., Drelich, J. W., & Vedani, M. (2018). Zinc-based alloys for degradable vascular stent applications. Acta Biomaterialia, 71, 1–23.

Munawar, A., Ong, Y., Schiragl, R., Tahir, M. A., Khan, W. S., & Bajwa, S. Z. (2019). Nanosensors for diagnosis with optical, electric and mechanical transducers. RSC Advances, 9(12), 6793–6803.

Musick, K. M., Coffey, A. C., & Irazoqui, P. P. (2010). Sensor to detect endothelialization on an active coronary stent. BioMedical Engineering Online, 9(1), 67. https://doi.org/10.1186/1475-925X-9-67

Nordrehaug, J. E., Wiseth, R., & Bønaa, K. H. (2016). Drug-eluting or bare-metal stents for coronary artery disease. New England Journal of Medicine, 375(26), 2602–2605.

Parche, J., Kastrati, A., Mehilli, J., Schühlen, H., Dotzer, F., Hausleiter, J., … Schöming, A. (2003). Intracoronary stenting and angiographic results: Strut thickness effect on restenosis outcome (ISAR-STEREO-2) trial. Journal of the American College of Cardiology, 41(8), 1283–1288.

Palmerini, T., Blomd-Zoccai, G., Della Riva, D., Mariani, A., Geneurex, P., Branzi, A., & Stone, G. W. (2013). Stent thrombosis with drug-eluting stents: Is the paradigm shifting? Journal of the American College of Cardiology, 62(21), 1915–1921.

Park, J., Kim, J.-K., Park, S. A., & Lee, D.-W. (2019). Biodegradable polymer material based smart stent: Wireless pressure sensor and 3D printed stent. Microelectronic Engineering, 206, 1–5.

Park, J., Kim, J.-K., Patil, J. S., Park, J.-K., Park, S., & Lee, D.-W. (2016). A wireless pressure sensor integrated with a biodegradable polymer stent for biomedical applications. Sensors, 16(6), 809.
Pendyala, L. K., Yin, X., Li, J., Chen, J. P., Chronos, N., & Hou, D. (2009). The first-generation drug-eluting stents and coronary endothelial dysfunction. *JACC: Cardiovascular Interventions, 2*(12), 1169–1177.

Piccolo, R., Bonaa, K. H., Efthimiou, O., Efthimiou, O., Varenne, O., Baldo, A., ... Valgimigli, M. ... (2019). Drug-eluting or bare-metal stents for percutaneous coronary intervention: A systematic review and individual patient data meta-analysis of randomised clinical trials. *The Lancet, 393*(10190), 2503–2510.

Räber, L., & Windecker, S. (2011). Current status of drug-eluting stents. *Cardiovascular Therapeutics, 29*(3), 176–189.

Roth, G. A., Johnson, C., Abajobir, A., Abd-Allah, F., Abera, S. F., Abyu, G., ... Murray, C. (2017). Global, regional, and national burden of cardiovascular diseases for 10 causes, 1990 to 2015. *Journal of the American College of Cardiology, 70*(1), 1–25.

Safar, M. E. (2018). Arterial stiffness as a risk factor for clinical hypertension. *Nature Reviews Cardiology, 15*(2), 97–105.

Sang, S., Cheng, P., Zhang, W., Li, P., Hu, J., Li, G., & Jian, A. (2014). Investigation on a new Fe83Ga17 wire-based magnetoelastic resonator biosensor. *Journal of Intelligent Material Systems and Structures, 26*(8), 980–987.

Serruys, P. W., Chevalier, B., Sotomi, Y., Cequier, A., Carrié, D., Piek, J. J., ... Onuma, Y. (2016). Comparison of an everolimus-eluting biodegradable scaffold with an everolimus-eluting metallic stent for the treatment of coronary artery stenosis (ABSORB II): A 3-year, randomised, controlled, single-blind, multicentre clinical trial. *The Lancet, 388*(10059), 2479–2491.

Shin, J., Liu, Z., Bai, W., Liu, Y., Yan, Y., Xue, Y., ... Rogers, J. A. (2019). Biodegradable optical sensor systems for monitoring of intracranial pressure and temperature. *Science Advances, 5*(7), eaaw1899.

Shittu, J., Sadeghilaridjani, M., Pole, M., Ayyagari, A., ... Mukherjee, S. (2020). Bio-electrochemical response to sense implant degradation. *Medical Devices & Sensors. http://dx.doi.org/10.1002/mds.310088*

Son, D., Lee, J., Lee, D. J., Ghaffarí, R., Yun, S., Kim, S. J., ... Kim, D.-H. (2015). Biodegradable electronic stent integrated with therapeutic nanoparticles for endovascular diseases. *ACS Nano, 9*(6), 5937–5946.

Takahata, K., Gianchandani, Y. B., & Wise, K. D. (2006). Micromachined antenna stents and cuffs for monitoring intraluminal pressure and flow. *Journal of Microelectromechanical Systems, 15*(5), 1289–1298.

Torii, S., Jinnouchi, H., Sakamoto, A., Kutyna, M., Cornelissen, A., Kuntz, S., ... Finn, A. V. (2020). Drug-eluting coronary stents: Insights from preclinical and pathology studies. *Nature Reviews Cardiology, 17*(1), 37–51.

Wen, P., Voshage, M., Jauer, L., Chen, Y., Qin, Y. U., Poprawe, R., & Schleifenbaum, J. H. (2018). Laser additive manufacturing of Zn metal parts for biodegradable applications: Processing, formation quality and mechanical properties. *Materials & Design, 155*, 36–45.

Yang, Q., Lee, S., Xue, Y., Yan, Y., Liu, T.-L., Kang, S.-K., ... Rogers, J. A. (2020). Materials, mechanics designs, and biodegradable multisensor platforms for pressure monitoring in the intracranial space. *Advanced Functional Materials, 30*(17), 1910718.

Ye, F., Lee, J., & Feng, P. X. L. (2017). Atomic layer MoS2-graphene van der Waals heterostructure nanomechanical resonators. *Nanoscale, 9*(46), 18208–18215.

Yeh, C.-C., Lo, S.-H., Xu, M.-X., & Yang, Y.-J. (2019). Fabrication of a flexible wireless pressure sensor for intravascular blood pressure monitoring. *Microelectronic Engineering, 213*, 55–61.

Zhoud, C., Keshavarz Hedayati, M., Zhu, X., Nielsen, F., Levy, U., & Kristensen, A. (2018). Optofluidic sensor for inline hemolysis detection on whole blood. *ACS Sensors, 3*(4), 784–791.

Zhu, S., Eldeeb, M. A., & Pang, S. W. (2020). 3D nanoplasmonic biosensor for detection of filopodia in cells. *Lab on a Chip, 20*, 2188–2196.