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Numerical investigation of stent designs for wireless access to integrated sensors

Abstract: In recent years, a progressive interest in the implementation of wireless access to cardiovascular implants has been established. This manifests in new devices, such as arterial pressure sensors, or additional functionalities added to established implants like stents. However, common stent designs, possessing highly optimized mechanical properties, often consist of cylindrically arranged struts with connections in-between which can be considered as short-circuited inductive coils. As a consequence, the small inductance raises the resonance frequency, which may decrease the *in vivo* performance of the wireless connection between the stent and the external readout device. Thus, new designs were developed to overcome this limitation, for example by avoiding the short-circuit due to a helical arrangement of the struts. Within this work we compare the performance of a common stent design and a helical design by means of numerical simulations. We are using two designs which only differ in the arrangement of the struts. The electromagnetic and mechanical properties are investigated using a finite-difference time-domain algorithm and finite element method, respectively. We will show that a common stent design exhibits resonance frequencies in the gigahertz regime, much higher than the frequencies of comparable helical designs. Furthermore, we compare the mechanical performance of the two designs and reveal individual distinctions in the radial stiffness, bending stiffness, and the von Mises stress.

Keywords: smart implant, inductive stent, helical stent, bending stiffness, radial stiffness, scattering cross section, finite-difference time-domain.

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1 Introduction

Providing wireless access to implants opens up new possibilities in early diagnosis and on demand therapies. Especially in the last year much progress was made in developing new passive *in vivo* sensor devices and integrating passive sensors in established implant technology. Thus, the intracranial pressure was measured *in vivo* and the possibility to measure strain and pressure within one biodegradable device was shown [1, 2].

Also in the field of interventional cardiology the recently developed devices concentrate on pressure measurements, for example in the pulmonary artery. But there are also efforts to integrate sensor technology into stents [3]. Such stents have to fulfill new requirements in addition to the originally intended purpose. They have to satisfy the mechanical requirements, but also need to provide wireless access and in consequence act as an electromagnetic resonator. Both, the mechanical as well as the electromagnetic properties, are highly influenced by the stent design.

Within this work we investigated a helical stent design in comparison to a conventional reference design by means of numerical simulations. The electromagnetic properties like resonance frequency and scattering cross section are calculated. And the differences in the mechanical properties like radial and bending stiffness are investigated.

2 Methods

2.1 Stent design

Generally, two types of designs were developed (cf. Figure 1), the helical stent and a reference stent, with lengths of 10, 20 and 30 mm respectively. The helix stent is based on an already investigated design [3]. The strut frame winds itself helically along the stent axis without any interconnecting stent links. The angle of the helix is 8° with a distance

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between the turns of 1.3 mm. The stent can therefore be considered as an induction coil [3,4]. The design is completed at both ends by struts which are wound transversely to the stent axis. They contain an area for sensor components, for example capacitive pressure sensors, which were not considered in this design.

The reference stent design is very similar to the helix design for an optimal comparison. All struts run transversely to the stent axis and are linked to the neighboring struts via three interconnecting bridges. A strut width and wall thickness of 90 μm as well as an inner diameter of 2.9 mm were assumed for all stents. The designs were generated using the computer-aided design software Creo Parametric 5.0 (PTC Inc., USA).

Figure 1: Comparison between helical and reference stent design. Two-dimensional representation of the design as well as the corresponding 3D artificial images.

2.2 Finite-element simulations

The mechanical properties of the stents were investigated using static structural mechanical analysis (ANSYS Mechanical 18.0, ANSYS Inc., USA). The stent material was modeled using a bilinear isotropic hardening model including the material parameters of structural steel: yield strength of 250 MPa and tangent modulus of 1450 MPa. For the calculation of the radial force the boundary conditions were chosen to prevent a tangential and axial movement of the stent. To obtain the bending stiffness, the struts, terminating the stent at one end, were fixed and the struts on the opposite end were deflected by 1 mm in maximum.

2.3 Finite-difference time-domain simulations

The electromagnetic properties of the stents were investigated using the open-source finite-difference time-domain solver openEMS v0.0.35 in combination with MATLAB R2018b (The MathWorks Inc., USA) for pre- and post-processing of the data [5]. A plane-wave polarized along the stent axis which has a Gaussian spectrum centered at 3 GHz (for the 30 mm long stent) and 5 GHz (for the 20 mm and 10 mm long stents) was used for excitation. The size of the mesh is chosen to have at least four full Yee cells within the struts. All stents are modeled as perfect conducting material.

3 Results and Discussion

3.1 Electromagnetic properties

The goal of the helical structure is to increase the inductance, realizing an easy adjustment of the resonance frequency as well as the concomitant possibility of sensing changes in the environment. However, the resonance frequency will highly depend on the actual sensing device included in the stent design. To investigate the resonance of the stent design possessing links interconnecting the struts windings the scattering cross sections of the reference designs were determined (cf. Figure 2).

Figure 2: Calculated scattering cross section of the reference stent design for a stent length of 10 (black), 20 (blue), and 30 mm (orange). The cross sections are normalized to the maximum of the 30 mm reference stent design.

The resonance frequencies of all three designs are located in the gigahertz regime. In addition, the frequency increases for shorter stents accompanied by a decreasing scattering cross section. A nearly doubling of the resonance frequency can be

observed when halving the stent length as expected from antenna theory for dipole antennas. Note that the calculated frequencies are two orders of magnitude higher than for helical stents including capacitive pressure sensors [3].

3.2 Mechanical properties

Within this work two main properties of stents were numerically investigated, the radial force-deformation characteristic as well as the bending stiffness. The radial force was determined for a 20 mm long stent of the helix and the reference design (cf. Figure 3). To obtain a radial deformation of 0.08 mm the force acting on the reference stent design has to be approximately twice as high as for the helical stent design. Thus, the radial stiffness in the elastic regime is clearly larger for the reference design. The geometric parameters, i.e. the material, strut dimensions, and stents dimensions, of the two designs are approximately the same, thus we assume that the variation of the radial stiffness is caused by the absent strut links and the helical shape.

Furthermore, we investigated the bending stiffness of the two designs. The deflection force as a function of the stent deflection is shown in Figure 4a and b for the reference and the helix design, respectively. Two effects become apparent: First, the helical design possesses a much smaller bending stiffness, i.e. for the same deflection the applied force is two orders of magnitude smaller. Second, as expected for both designs the short stents require a larger force to obtain a certain deflection than the long stents. In addition, the distribution of the von Mises stress on the stents differs for both designs. The von Mises stress for the 20 mm helix and reference stent is shown in Figure 4. A nearly homogeneous

stress distribution can be found for the reference design (cf. Figure 4a). The maxima of the stress are predominantly located at the connectors between the transversely running struts.

Figure 3: Radial force as a function of the radial stent deformation, calculated for the 20 mm long helical stent design and the 20 mm long reference stent design.

In contrast, the helix design shows a relative inhomogeneous stress distribution, located at both ends of the helix. Such a distribution is observed for all stent lengths of this particular design. The connection points between the helix and the transversely running struts are the same for all stent lengths. In consequence, the difference in the stress distribution, which may be caused by the missing interconnecting strut links, could be the reason for the large variation in the bending stiffness.

Figure 4: Calculated von Mises stress for the 20 mm reference stent design (a) and the 20 mm helical stent design (b) as well as the deflection force for the 10, 20, and 30 mm long reference (a) and helix stent designs (b).

4 Conclusion

Within this work we developed two stent designs, a helix and a reference design, to allow for a direct comparison of the mechanical properties between a helical (inductive) stent and conventional (reference) design possessing interconnected struts. We observed a much larger radial stability of the reference stent compared to the helix design. The investigation of the stent deflection showed a difference of at least two orders of magnitude in the bending stiffness of the two stent designs. We assume the origin of this effect is the stress distribution during deflection, which is very inhomogeneous for the helical stent compared to the reference and located at the connection between the helix and the transversely oriented struts.

Furthermore, we showed that the electromagnetic resonances of the reference design are located in the gigahertz regime and follow a shift associated with the stent length as expected from antenna theory.

This study provides new insights in the properties of inductive and conventional stents, which is essential for the investigation of competitive new stents with wireless accessible features.

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References

- [1] Chen LY, Tee C-K, Chortos AL, Schwartz G, Tse V, Lipomi DJ, Wong H-SP, McConnell MV, Bao Z. Continuous wireless pressure monitoring and mapping with ultra-small passive sensors for health monitoring and critical care. *Nat. Commun.* 2014; 5:5028.
- [2] Bourty CM, Kaizawa Y, Schroeder BC, Chortos A, Legrand A, Wang Z, Chang J, Fox P, Bao Z. A stretchable and biodegradable strain and pressure sensor for orthopaedic application. *Nat. Electron.* 2018; 1:314-321.
- [3] Mohammadi AR, Mohamed Ali MS, Lappin D, Schlosser C, Takahata K. Inductive antenna stent: design, fabrication and characterization. *J. Micromechanics Microengineering.* 2013; 23:025015.
- [4] Chen X, Assadsangabi B, Hsiang Y, Takahata K. Enabling Angioplasty-Ready "Smart" Stents to Detect In-Stent Restenosis and Occlusion. *Adv. Sci.* 2018;5:1700560
- [5] Liebig T, openEMS - Open Electromagnetic Field Solver, General and Theoretical Electrical Engineering (ATE), University of Duisburg-Essen, <https://www.openEMS.de>.