Microwave spectrometry for non-invasive stent monitoring using near-field probes.

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Abstract: The aim of this work has been to characterize the capabilities of different probes to detect structural and enviromental changes in a stent through microwave spectrometry. We begin comparing the stent detection capabilities of four near-field probes (named as Brass, Half-MoonG, Origin and Magnetic probes) by distancing and misalingning a stent sunken in distilled water. The two probes which perform better (Origin and Magnetic probes) are used to conduct a more in-depth study of their detection capabilities in open-air conditions. Stent detection at large distances (1.5cm) is only achieved by Magnetic probe. Tolerance to stent misalignments is also greater with Magnetic probe. Subsequently, we analyse the capacity of these two probes to detect changes in the stent length (fractures) in open-air conditions. Three stents are used to perform fractures at three different points of their total length; three types of fracture are analysed in each stent. Both probes discern each fracture type, regardless the point where it is performed, and exhibit results in agreement with theoretical predictions. Similarly, we analyse the capacity of these two probes to detect changes in the stent vicinity (restenosis). Artery segments of different lengths are inserted to mimic restenosis into a stent wrapped inside another artery of larger diameter. The results obtained have been compromised by changes in the water content of the arteries.

I. INTRODUCTION

A stent is a medical prosthetic device shaped as a small cylindrical tube with wire mesh walls, which is used to revascularize atherosclerotic stenosed blood vessels [1]. The introduction of bare metal stents has markedly increased the success rate of previous revascularization techniques, mainly angioplasty.

Despite the advances in percutaneous coronary interventions [2, 3], some of the original complications persist after stenting and some others emerge from this procedure. One of the main concerns is "restenosis", the recurrent obstruction at the stent implantation site. Stent structural damage, such as fractures, represent a risk factor for restenosis and other complications. To avoid these problems, patients are subjected to chronic medication and should be monitored regularly.

However, stent monitoring requires ionizing or invasive tools such as X-ray angiography, intravascular ultrasound and optical coherence tomography. Given the negative impact that these techniques have on the patient, their application must be justified, which considerably restricts the monitoring of patients with stents. Microwave-based techniques are non-ionizing and non- invasive [4], and so they are particularly suitable for a more thorough follow-up of the patient.

Our microwave-based spectrometry (MWS) method is based on a resonance phenomenon. Alike a half-wavelength dipole antenna, a resonance should occur at those frequencies at which the stent length is a multiple of half the guided wavelength of the modes propagating along the stent. Other structural characteristics such as stent diameter and architecture do not determine the characteristic resonance frequency order but must also be considered [5].

During this work, we will characterize the capacity of near-field probes to detect structural and enviromental changes in a stent through microwave spectrometry by performing four experiments. In the first place, we will make a comparison of the probes in distilled water in order to select the most capable probes for the subsequent experiments (Probe comparison). After determining the probes that performed better, we will make an experiment in open-air conditions to characterize them, that is, to see their tolerance to probe-stent distance variations and stent misalignments (Probe characterization). Afterwards, we will study if the probes were able to detect different types of fractures in the stent (Fracture experiment). Finally, we will analyse if the probes could detect the formation of restenosis in a stent (Restenosis experiment).

II. EXPERIMENTAL METHODS

A. Microwave spectrometry set up and equipment

To carry out the following experiments we had at our disposal four near-field probes. Three electrical probes (named as Brass, Half-MoonG and Origin probes) and a magnetic probe (named as Magnetic probe). A frequency swept measurement of the transmission coefficient between the probe and the stent should have local maxima caused by the resonances of the stent.

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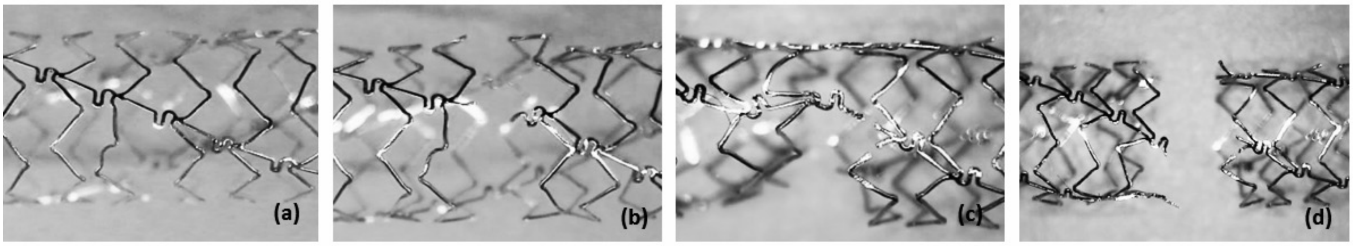

FIG. 1: Images of the different types of fractures performed in the stent. (a) no fracture stent (b) strut fracture (Type I); (c) half-crown fracture (Type II); (d) complete fracture (Type III).

The MWS characterization was performed by placing the stent right under the probe with the aid of a vertical column of expanded polystyrene. This vertical column was mounted on a unipolar stepping motor conforming a column-stepper assembly. The assembly allows rotation of the stent by an azimuthal angle ($\alpha(^o)$) around an axis that is perpendicular to the centre of the probe. The motor was connected to a single board microcontroller (Arduino Uno, Interaction Design Institute Ivrea) through a home-built circuit, and the microcontroller was directly connected to a computer. Concurrently, the column-stepper assembly rested on a mobile platform that allows variation of the distance among the stent and the probe (from now on, probe-stent distance h_i (mm)).

A network analyzer was also connected to the computer to perform a frequency swept measurement of the transmission coefficient between the probe and the stent. The whole system was controlled by means of a home-made program (Lab-VIEW, National Instruments Corporation).

B. Probe comparison

In order to unearth the probes with the best performance, we carried out tests in distilled water. Both the tolerance of each probe to large probe-stent distances and the tolerance to probe-stent misalignments were compared. To parametrize the probe-stent distance tolerance we placed a stent at: $h_1 = 1mm$, $h_2 = 6mm$ and $h_3 = 11mm$. For each distance, the stent was rotated around the axis perpendicular to the centre of the probe to parametrize the probe-stent misalignment by: $\alpha = 0^o$ and $\alpha = 45^o$. The experiment was carried out using an Architect (iVascular SLU) stent model with $p_{nom} = 7atm$ ($l_{nom} = 19mm$, $d_{nom} = 2mm$), expanded up to $p = 7atm$ ($l = 18.89mm$, $d = 1.79mm$).

C. Probe characterization

A more in-depth study of the detection tolerances to probe-stent distance and misalignments of two probes (Origin and Magnetic probes) was performed in open-air conditions. We also used an Architect stent model $p_{nom} = 7atm$ ($l_{nom} = 19mm$, $d_{nom} = 2mm$), expanded up to $p = 7atm$ ($l = 18.89mm$, $d = 1.79mm$). Probe-stent distances were specifically selected for each probe by the following relation: $\frac{n \cdot h_{max}}{4}$ where $n = 1, 2, 3, 4$. Therefore, Origin probe was measured at: $h_1 = 2mm$, $h_2 = 5mm$, $h_3 = 7mm$ and $h_4 = 10mm$. Whereas Magnetic probe was measured at: $h_1 = 3mm$, $h_2 = 7mm$, $h_3 = 11mm$ and $h_4 = 15mm$. As in the Probe comparison section, the stent was misaligned a certain α at each distance. In this experiment however, the stent was rotated from $\alpha = 0^o$ to $\alpha = 180^o$ with both probes. The rotation range was covered in steps of 1,8 (which corresponds to the minimum rotation the motor can perform).

D. Fracture experiment

We analysed the capacity of Origin and Magnetic probes to detect changes in the stent length in open-air conditions by simulating three types of stent fractures. We used three Architect stents with $p_{nom} = 11atm$ ($l_{nom} = 19mm$, $d_{nom} = 4mm$) that were expanded up to $p = 9atm$ ($l = 18.91mm$, $d = 3.89mm$). In the first stent we piecemeal performed three cuts at $l/5$ using a customized precision plier and a hand lens, Likewise, in the second stent the three cuts were performed at $l/3$ while in the third one the cuts were performed at $l/2$. The first cut simulated a strut fracture (Type I); the second cut simulated a half-crown fracture (Type II); and the third cut, which utterly separated the stent into two segments, simulated a complete fracture (Type III); the three types of cuts could be seen in Figure 1. After the completion of each cut, the transmission coefficient was acquired. To perform such acquisition, the stent was placed right under the probe at minimum distance (h 0 mm) aligned at 0^o degrees on the Origin probe and at 45^o degrees on the Magnetic probe.

E. Restenosis experiment

Finally, we analysed the capacity of Origin and Magnetic probes to detect changes in the stent vicinity in open-air conditions by simulating restenosis. We

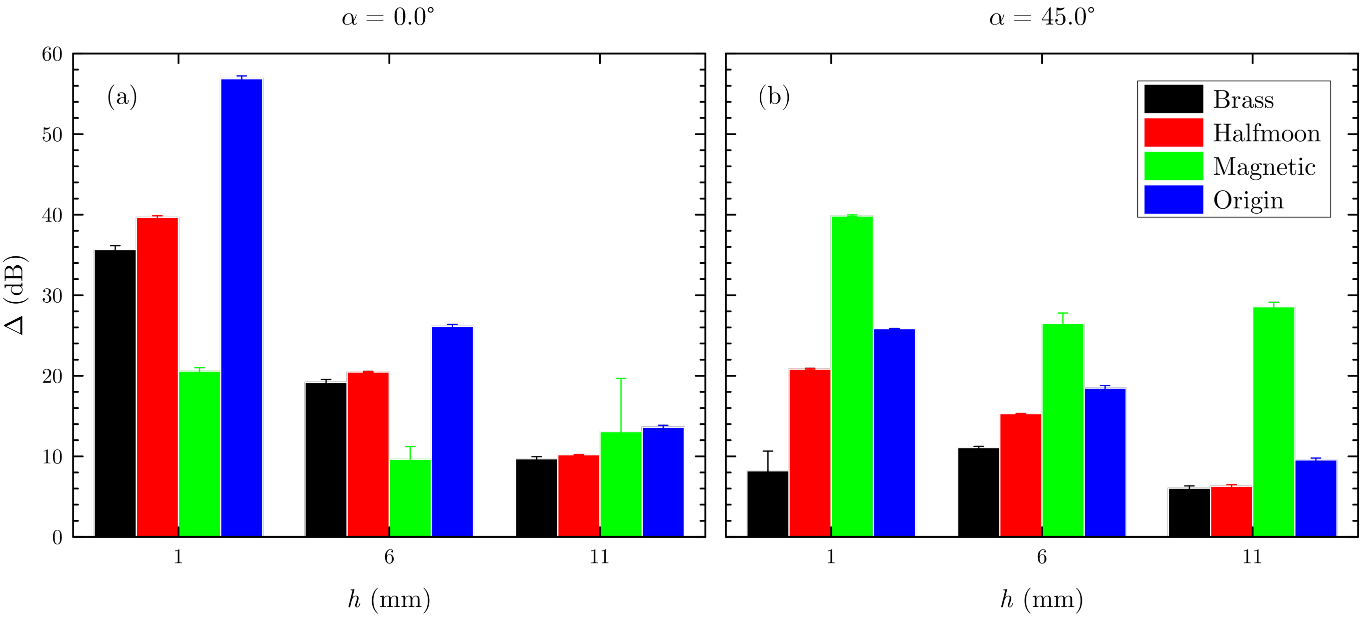

FIG. 2: Diagram of the variation of dB with respect to the basal measure as a function of probe-stent distance (h(mm)) and misalignment ($\alpha(^o)$) : (a) $\alpha = 0^o$; (b) $\alpha = 45^o$.

used a Coroflex (B. Braun) stent with $p_{nom} = 10atm$ ($l_{nom} = 19mm$, $d_{nom} = 3.5mm$) that was expanded up to $p = 6atm$ ($l = 18.76mm$, $d = 2.78mm$) to adjust its diameter to that of the artery. In order to simulate several states of restenosis, we gradually cut an artery fragment at lengths: l, $l/2$, $l/3$ and $l/4$. After each cut the fragment was placed inside the stent and positioned first towards the edge and afterwards in the center of the stent. For each situation and with each probe, we acquired the transmission coefficient placing the wrapped restenotic stent at the minimum probe-stent distance (h$\approx$ 0 mm) aligned at 0^o degrees on the Origin probe and at 45^o degrees on the Magnetic probe.

III. RESULTS AND DISCUSSION

A. Probe comparison.

As it can be seen in Figure 2, the best performance at large probe-stent distances and whether the stent is misaligned or not has been achieved by Origin and Magnetic probes.

Beforehand, Magnetic probe appears to have a greater tolerance to large probe-stent distances than the Origin probe. Moreover, it seems to have a greater tolerance to stent misalignments too. It must be highlighted however that there is an optimal α_0, at which the stent is not misaligned, for each probe. This ideal α_0 is 0^o (and 180^o) for the Origin probe and 45^o (and 135^o) for the Magnetic probe. Consequently, the closer the misalignment α is to this optimal α_0 the better the probe performance will be.

On the other hand, both Origin and Magnetic probes can be flexible; an advantage that would facilitate the measurements on a patient as the probes would be able to adapt better to the body shape.

Taking into account these results, we conducted a more in-depth study with Origin and Magnetic probes.

B. Probe characterization

Figure 3 shows the frequency diagram where the angular and height dependence of each probe is observed. We can appreciate the resonance around $f \approx 5GHz$. The black lines observed in the images correspond to an antiresonance, which remains to be studied.

In the first place we can see the clear dependence on the probe-stent distance of both probes. The greater the distance between the probe and the stent, the less signal the probes perceive.

Although both probes have a decrease in the acquisition of the signal with the distance, this decrease is not equal in both of them. In Figure c1 and b2 the distance of the stent relative to the probe is the same, however, in b2 the resonance is clearer than in c1. The same happens if we compare Figures d1 and c2. In d1 is practically impossible to observe the resonance; we are at the maximum tolerated distance of the Origin probe, $h_4^{Ogn} = 10mm$. On the other hand, in Figure c2 the maximum tolerated distance between the stent and the probe is $h_3^{Mag} = 11mm$, greater than the maximum tolerated distance of the Origin probe, but in this case we still can perceive the resonance. For greater distances, the Magnetic probe performes better, since the maximum probe-stent distance at which the stent can be detected is greater than in the Origin probe.

In the Origin probe a clear angular dependence is seen: the more the stent is misaligned with respect to the original position ($\alpha = 0^o$) the worse the resonance is detected. However, in the Magnetic probe the angular dependence is minimal, the resonance seems to be perceive at any orientations.

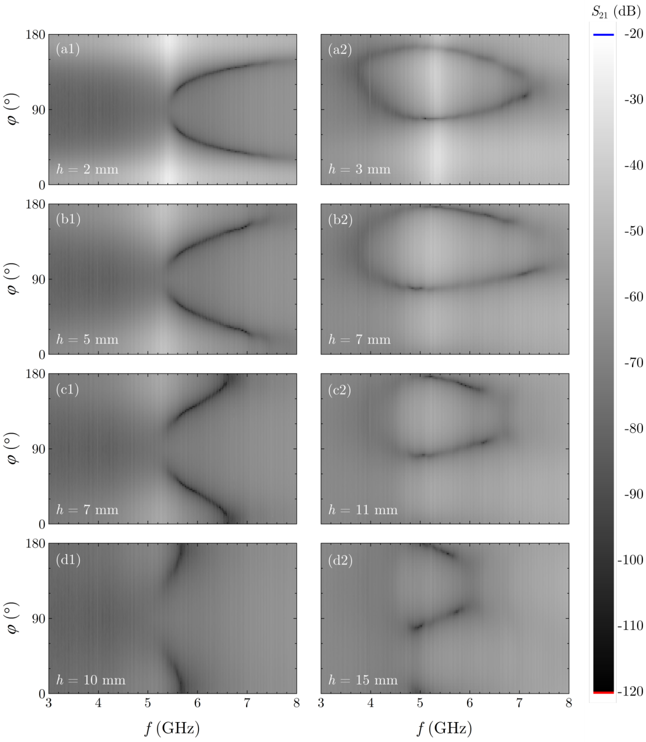

FIG. 3: Resonance frequency diagram showing probe-stent angular, ($\phi(^o)$), and distance dependence ,(h (mm)), performed by Origin (a1, b1, c1, d1) and Magnetic probe (a2, b2, c2, d2).

C. Fracture experiment

The results obtained are shown in Figure 4, which exhibit the relative frequency variation due to each of the fractures.

Based on Figure 4, we can see that Type I and Type II fractures result in a downshift of the resonance frequency with respect to the value for the unaltered stent. According to these results, one might think that when cutting the stent there was a certain deformation that increased in some way the length, l, resulting in this frequency decrease [5].

A possible explanation for the frequency downshift is that as the path that followed the field to reach from one edge to another is truncated, it is compelled to take another way larger. This fact could be understood as an increase in the length of the stent, and therefore, as a decrease of the frequency.

On the other hand, Type III fracture results in an upshift of the resonance frequency. As mentioned above, Type III fracture cuts the stent into two completely separate parts, which implies that once the cut is done, we have two stents of smaller lengths than the original stent. Since the resonance frequency is inversely proportional to the length, if the probe detects a stent of shorter length, the resonance frequency will be higher.

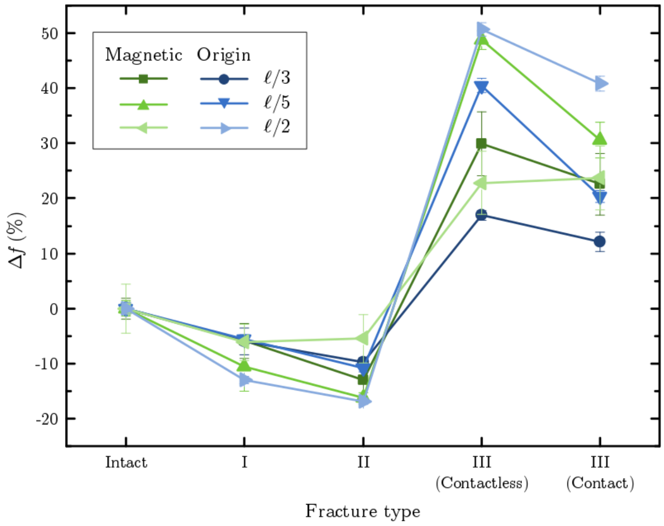

FIG. 4: Relative frequency varition as a function of the type of fracture (Type I, Type II or Type III) for each length ($l/2, l/3, l/5$) and probe (Origin and Magnetic probe).

D. Restenosis experiment

In carrying out this test it was expected that, the longer the artery piece placed in the stent, the greater the downshift in the resonance frequency. However, an opposite effect is seen after the measurements: an upshift in the resonance frequency which is greater on the smaller restenosis artery pieces. This upshift is smaller for the first measurements taken and becomes greater for the last measurements taken.

It is important to note that, during the experiment, the arteries, being in continuous contact with the air, were progressively drying and losing moisture. Since the resonance frequency depends on the permitivity of the medium, which, was not stable during the experiment, each probe measured the stent under different conditions. Specifically, those mesurements taken after a certain amount of time will show better probe capabilities. Therefore, this upshift is probably related to the water content of the artery. Moreover, if any restenosis effect can be measured with the probe, this water content loss is covering it up. Hence, in this document a conclusion can not be obtained about which one of the probes is the most capable to distinguis restenosis.

IV. CONCLUSIONS

Throughout this work we have characterized the capability of the near-field probes to detect changes in a stent using MWS in distilled water and in open-air conditions. In the first place, we discovered that the probes which perfromed better were Origin and Magnetic probes. In the second place, we observed that Magnetic probe has greater tolerance to large probe-stent distances than Origin probe and, in addition, it has greater tolerance to stent misalignments too. Finally, we have proven that the aforementioned probes detect the different types of fractures that can occur in a stent. However, restenosis results are not valid and therefore do not allow us to conclude that this near-field probes detect restenosis.

The results are promising, but more experiments should be carried out. Despite the fact that we have been able to verify that the probes perform as expected in distilled water and air conditions, we should see if they do so in animal tissue and other biological materials as well. Among the future experiments restenosis test should be repeated, this time however, preventing the arteries from losing moisture. It would also be interesting to repeat the fracture experiments in larger stents so as to delve into the correlation of resonance frequency and stent length. Last, but not least, an analysis of the antiresonance shown in the Figure 3 should be done with the purpose of understanding its nature.

V. REFERENCES

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