Multifunctional 3D Printed Piezoelectric Smart Stent

Sayemul Islam, Jun Ying Tan, Jungkwun Kim, and Albert Kim.

This abstract presents a 3D-printed piezoelectric smart stent for a self-energized, in-situ, real-time blood flow and pressure measurement scheme. The proposed system can be used for wireless continuous post-endovascular aneurysm repair (EVAR) monitoring. Endovascular aneurysm refers to an abnormal bulge on the blood vessel often leading to rapture or bursting which may require immediate surgical interventions [1]. Common EVAR method includes open surgery or endovascular repair by placing a stent graft in the affected area using minimally invasive surgery to normalize blood flow and relieve pressure from the artery wall. Delays in treatment can lead to blood clots, endoleaks, deep vein thrombosis or health attacks, etc. However, several complications can happen even after a successful EVAR surgery (i.e., endoleaks type I-V, endograft infection, endograft collapse, ischemia, etc.). Therefore, continuous monitoring can be useful to prevent such incidents. Common post-EVAR monitoring method includes Radiography, Computed Tomography (CT), Magnetic Resonance Angiography (MRA), Ultrasonography, Nuclear Imaging, etc. These methods are often expensive, have limited availability, are invasive, or are sometimes unable to detect major issues such as endoleaks [2]. Therefore, we propose the 3D printed polymer-based piezoelectric smart stent that can function as a traditional stent while providing in situ sensing.

The proposed smart stent can be fabricated using a 3D printer with PVDF-TrFE (polyvinylidene fluoride-co-trifluoroethylene) 70/30 mol copolymer filament (melting 145 °C, Curie temperature 95 °C) (PolyK Technologies). PVDF-TrFE copolymer was chosen over piezoelectric polymer PVDF because PVDF-TrFE belongs in beta ferroelectric phase, which is relatively easier to pole for piezoelectric response (poling field V/µm < 30% of PVDF) during 3D printing [3]. When it is used as a stent, the piezoelectric response due to the mechanical stress induced by the blood flow and pressure can be harvested as electrical energy, making it a self-energized sensor device [4]. Fig 1. shows a conceptual drawing of the proposed 3D printed self-energized smart stent compared to a traditional wire stent working as an in-situ blood flow and pressure sensor.

Fig. 2 shows the 3D printing and in-situ high-voltage poling method which is adapted from the work of Alec et al. [5]. Several 3D printing settings have been experimented with to achieve the optimum printing output. For our case, a print temperature of 205 °C with a print bed temperature of 90 °C produced the best quality single-layer piezoelectric film. The PVDF-TrFE film was printed directly onto the build plate using a customized 3D printer (MK3S+, Prusa). After printing, it was later rolled and jointed using a heat press to complete the proposed stent. The diameter and length of the rolled film was 15 mm and 25 mm respectively. The fabrication method is shown in Fig. 3. The PVDF-TrFE film was printed with different patterns to increase sensitivity and average voltage output [6]. The layer thickness and the line width were 0.4 mm during the printing. After printing, an electrode layer was applied on both sides using electrically conductive silver epoxy (AA-Duct 907, Atom Adhesives) to collect piezoelectric charges. Roller brush technique was used to achieve a thin and uniform layer of electrode (50 ± 5 µm on each side). The silver epoxy electrode layer was cured at 60 °C for 60 minutes. The piezoelectric charge constant (d_{33}) was measured using a Berlincourt Piezoelectric meter (PKD3-2000-F10N, PolyK Technologies) for each sample to confirm piezoelectricity under mechanical stress. During the d_{33} measurement, the applied static force was carefully maintained at 2 ± 0.05 N and the applied dynamic force was at 250 ± 10 mN. The d_{33} constant is expected to average at 6 pC/N. Fig. 4 shows the proof-of-concept piezoelectric 3D printed smart stent compared to a traditional stent (e.g., FEM 14060, Fluency Plus Endovascular Stent Graft).

Fig. 5 shows the experiment setup where the smart stent is placed in the aortic vessel replicating a closed-loop blood flow mimicking fluid dynamic to evaluate its sensing and energy harvesting capabilities. A continuous mode peristaltic pump (Kamoer AIP) with DI water was used for the flow experiment. The artery pressure was monitored by an in-situ blood pressure sensor (BP0001, Merit Sensor) on the artery vessel and validated by a calibrated pressure transducer on the connecting tube (DPG210-005G, Omega). The artery vessel was prepared using soft polymer (Ecoflex-50). The blood flow rate was monitored by commercially available flow meters to maintain the flow rate between 4-6 liter/min (mimicking actual blood flow in the aorta). The output of the smart stent was measured by an oscilloscope (DSOX3034G, Keysight) for different flow rates controlled by the peristaltic pump. Corresponding vessel pressure was also recorded during the experiment.

The proposed smart stent demonstrates that traditional stents can be created using a 3D printer using piezoelectric PVDF-TrFE filaments. It can be used for detecting variations in the blood flow rate or pressure. It also has the potential to harvest energy from blood flow in the human body, which may energize onboard electronics to transmit that information in the future.

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References

[1] G. Maleux, M. Koolen, and S. Heye, "Complications after endovascular aneurysm repair," *Semin Intervent Radiol,* vol. 26, no. 1, pp. 3-9, Mar 2009. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/21326525.

[2] D. Daye and T. G. Walker, "Complications of endovascular aneurysm repair of the thoracic and abdominal aorta: evaluation and management," *Cardiovasc Diagn Ther,* vol. 8, no. Suppl 1, pp. S138-S156, Apr 2018, doi: 10.21037/cdt.2017.09.17.

[3] A. Ikei, J. Wissman, K. Sampath, G. Yesner, and S. N. Qadri, "Tunable In Situ 3D-Printed PVDF-TrFE Piezoelectric

Arrays," *Sensors (Basel),* vol. 21, no. 15, Jul 24 2021, doi: 10.3390/s21155032.

[4] S. Islam, X. Song, E. T. Choi, J. Kim, H. Liu, and A. Kim, "In Vitro Study on Smart Stent for Autonomous Post-Endovascular Aneurysm Repair Surveillance," *IEEE Access,* vol. 8, pp. 96340-96346, 2020, doi: 10.1109/ACCESS.2020.2996506.

[5] Alec Ikei, James Wissman, Charles Rohde, and G. Yesner, "3D Printed PVDF," U. S. NAVAL RESEARCH LABORATORY, NRL Memorandum Report NRL/MR/7165--20-10,123, 9/30/2020 2021.

[6] J. Y. Tan, S. Islam, Y. Li, A. Kim, and J. Kim, "An Optimization of Perforation Design on a Piezoelectric-Based Smart Stent for Blood Pressure Monitoring and Low-Frequency Vibrational Energy Harvesting," in *2023 IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS)*, Munich, Germany, 2023.

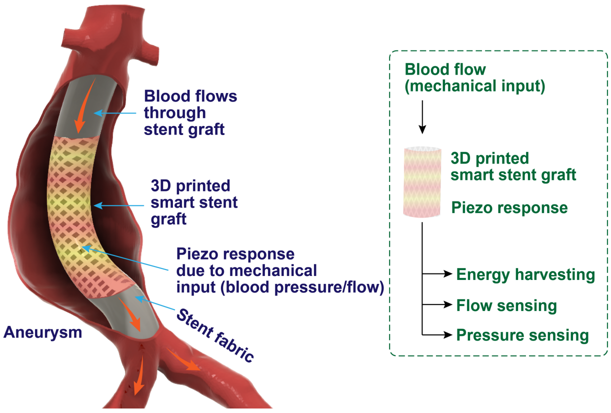

Figure 1. *3D printed self-energized smart stent incorporated with a traditional stent fabric working as an in-situ blood flow and pressure sensor*

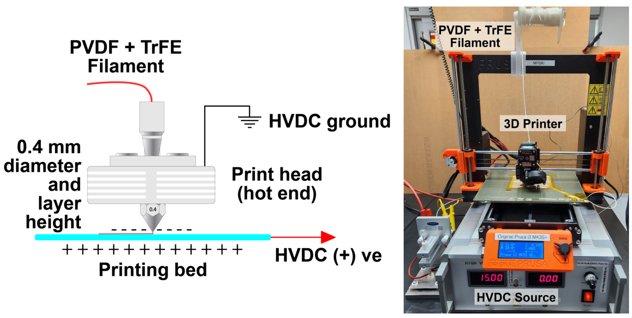

Figure 2. *3D printing PVDF-TrFE material with in-situ high voltage (HVDC) poling to create piezoelectric stent*

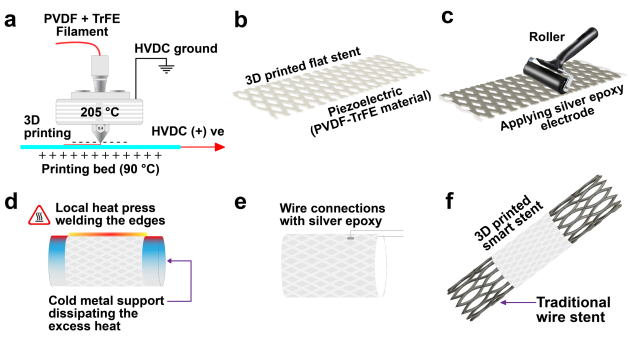

Figure 3. *Fabrication method of 3D printed smart stent: (a) 3D printing with in-situ high voltage poling, (b) 3D printed smart stent, (c) manually applying conductive silver epoxy as top and bottom electrode layer using a roller, (d) welding end part of flat print to make it a cylindrical shape using heat press, (e) making necessary wire connections using silver epoxy, (f) 3D printed stent incorporated with a traditional wire stent*

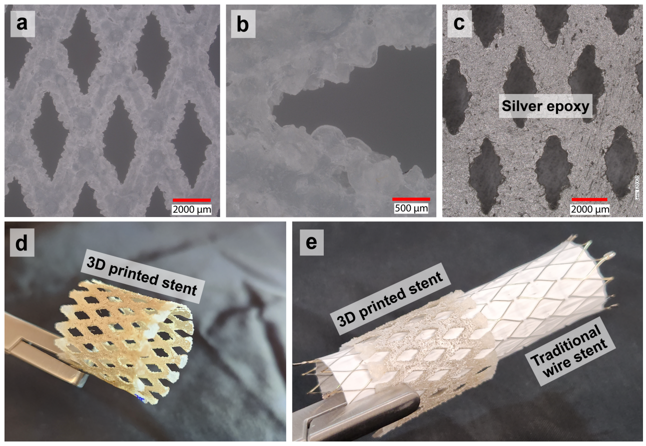

Figure 4. *Prototype 3D printed stent: (a) and (b) magnified image showing the 3D prints before adding electrodes, (c) silver epoxy electrode layer, (d) rolled stent, (e) PVDF-TrFE 3D printed stent incorporated with a traditional stent*

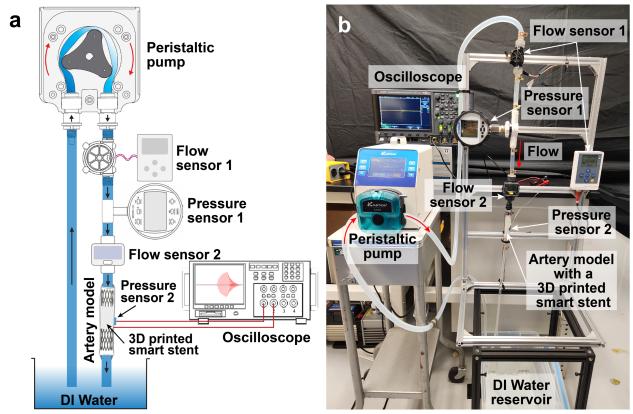

Figure 5. *Closed-loop circulation experiment setup with artery model: (a) simplified flow diagram, (b) laboratory experiment setup*