Development of IR-based needle tip location estimation for Self-Cannulation

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Introduction: End-stage kidney disease (EKSD) is the final, permanent stage of chronic kidney disease (CKD), where the body's kidney cannot filter blood sufficiently. Dialysis treats ESKD by filtering wastes and water from your blood externally via a dialyzer [1]. Patients on hemodialysis require vascular access (an arteriovenous fistula (AVF) or graft (AVG)) for dialysis [1]. They go through this process typically about three times a week for about 4 hours a session, which is quite tedious, especially for elderly patients and patients with co-morbidities. Therefore, patients with end-stage kidney disease often opt for home hemodialysis (HHD) and face the significant challenge of learning to self-cannulate their arteriovenous access [2]. Self-Cannulation is a skill that requires comprehensive training at one's own learning speed. Our current cannulation skills training simulator is limited in terms of portability and affordability, due to the size and high cost ($8000) of the electromagnetic (EM) motion tracking system which is used to estimate the location of the needle tip inside the AV fistula [3]. Therefore, making our current simulator less feasible for a self-cannulation training simulator setup. So, in order to make our training simulator more feasible in terms of size and affordability, especially for self-cannulation skills training, we decided to develop an IR- emitter- detector-based system to estimate the location of the needle tip inside the AV fistula. Moreover, an ideal self-cannulation simulator necessitates a way to accurately provide real-time needle location estimations. Our goal is to estimate the location of the needle using our IR-based system with at least a 90% accuracy. Achieving this goal on our current fistula dimensions means estimating the position of the tip of the needle needs to be accurate for at least 81 mm along the total 90 mm length of the fistula.

Methods: In order to develop an IR-based system to estimate the location of the needle tip inside the AV fistula, we first fabricated an IR detector at the tip of a 15-G needle. Four IR emitters were fabricated at equal distances (15 mm) from each other on a flex board and placed inside our AV fistula. The four IR emitters are actuated at four different frequencies (30Hz, 340Hz, 730Hz, and 1200Hz). A 4th order narrow bandpass (single frequency) filter circuit was created in order to filter out the 4 frequencies of the IR emitters. The reading outputted by the IR detector sensor is passed through the filter circuit yielding four independent voltages corresponding to the amount of IR detected from each emitter. The four output voltages from the filter circuit are a function of the needle's proximity toward the 4 IR emitters.

Results: In order to prove the IR-based needle tip location estimation concept works, we designed an experiment to test the system while the needle is moving freely in 1-D i.e., keeping the y-direction and the z-direction of the needle motion constant and just varying the x-direction of the needle motion. This experiment showed that the developed system is capable of accurately detecting the location of the needle tip in near real-time in 95.56% of the length of the fistula model. The parts where the needle tip was not accurately located consisted of only 4 mm out of 90 mm.

[1] C. E. Lok et al., "KDOQI Clinical Practice Guideline for Vascular Access: 2019 Update," Am. J. Kidney Dis., vol. 75, no. 4, pp. S1–S164, Apr. 2020, doi: 10.1053/j.ajkd.2019.12.001.

[2] United States Renal Data System. 2021 USRDS Annual Data Report: Epidemiology of kidney disease in the United States. National Institutes of Health, National Institute of Diabetes and Digestive and Kidney Diseases, Bethesda, MD, 2021.

[3] Z. Liu *et al.*, "Measuring Cannulation Skills for Hemodialysis: Objective Versus Subjective Assessment," *Front. Med.*, vol. 8, p. 2291, 2021, doi: 10.3389/fmed.2021.777186.