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# Multi-Wavelength Crosstalk-Free Photonic Doppler Velocimetry

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**Abstract.** Multiplexed Photonic Doppler Velocimetry systems are developed to measure velocities with high density in physics experiments such as shock physics on novel materials. Decreasing the mesh size can lead to crosstalk issues which can be overcome by wavelength multiplexing. Crosstalk has been characterized on a line of 8 collimators with a pitch of 1 mm. A crosstalk-free Photonic Doppler Velocimetry system with 16 telecom wavelengths was built. Wavelength multiplexing provides as well a reduction of the total number of fiber components. The system was designed for velocities up to 1000 m/s and with a bandwidth of 2 GHz. In the frequency domain, the channel spacing is 100 GHz which is more than enough to prevent any crosstalk. A ramp compression experiment was carried out by a high-pulsed-power generator to demonstrate the dynamic performances of the cross-talk free system at about 80 m/s.

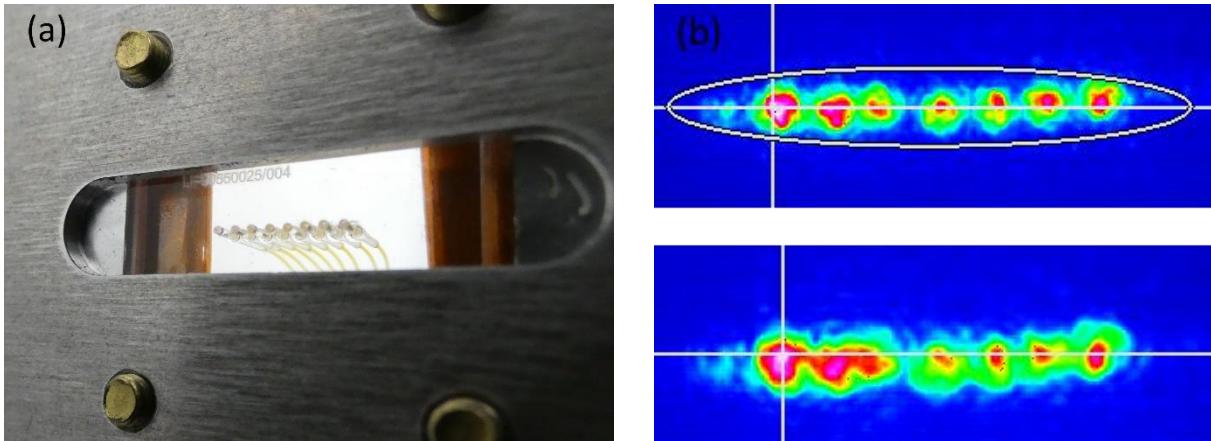
## INTRODUCTION

Laser Doppler Velocimetry (LDV) started in the middle of the sixties with the frequency shift measurement of a He-Ne laser through a liquid excited by an ultrasonic wave<sup>1</sup>. Right after, flow velocities measurements of gases and liquids were reported<sup>2,3</sup>. Velocities measurements to study the dynamic mechanical properties of materials were also initiated in the middle of the sixties<sup>4</sup>. Few years later, the VISAR<sup>5</sup> (Velocity Interferometer System for Any Reflector) became more and more available and is since used for shock physics on novel materials. Since 2000, compacter fiber-based systems known as Photonic Doppler Velocimetry (PDV)<sup>6,7</sup> systems are being used. High speed PDV systems (up to 10 km/s) use directly Short-Time Fourier Transform (STFT) for the signal processing of the Doppler fringes. When the time resolution gets too limited by the interference fringe size, slightly modified PDV systems are used with a signal processing based on phase analysis<sup>8-10</sup>. The latest PDV developments were mostly driven by the need of high density measurements on a target with more than one hundred channels. The mix of frequency-mixing (x4 or x8 factor) and time-multiplexing (x2 or x4 factor) by optical fiber storage were reported<sup>11,12</sup> which leads to systems with 64 channels recorded on a single oscilloscope with 4 inputs. A 32 channels PDV system using only time-multiplexing (x8) was reported<sup>13</sup> in which 7 delay lines are timely sequenced by fast optical switches. The increase in the number of channels could create crosstalk issues if the physical spacing between the measurement points gets closer. The crosstalk depends on the optic and on the targeted surface quality. Optical diffusion spreads the reflected beam and adjacent signals can be mixed. It is particularly the case on 3D carbon materials<sup>14</sup>. This crosstalk issue can be cancelled by wavelength multiplexing if the channel spacing is greater than the maximum Doppler frequency. Looking more carefully at the system design of Daykin<sup>12</sup>, wavelength multiplexing with 4 channels was used twice for the base and local oscillator lasers. The possible crosstalk issue was briefly mentioned but the paper was more focused on how to increase the number of channels. The telecom multiplexers-demultiplexers (AWGs - Arrayed Waveguide Gratings<sup>15</sup>) used routed the 4 probes signals on 4 different delays without any switch and the associated electronics. In this paper, we present a 16 channel multiplexed crosstalk-free PDV system without any local oscillator lasers. Crosstalk has been characterized on a line of 8 collimators spaced by 1 mm. This system is designed to be used in ramp compression

experiments generated by high-pulsed-power (HPP) generators<sup>16-18</sup> in which the velocities are typically below 1000 m/s. Nevertheless, with faster photoreceivers and higher bandwidth digitizers, the same scheme could work at much higher velocities. Our multi-wavelength system was successfully validated with 4 wavelengths intentionally grouped in a single collimator pointing to a surface moving at ~80 m/s.

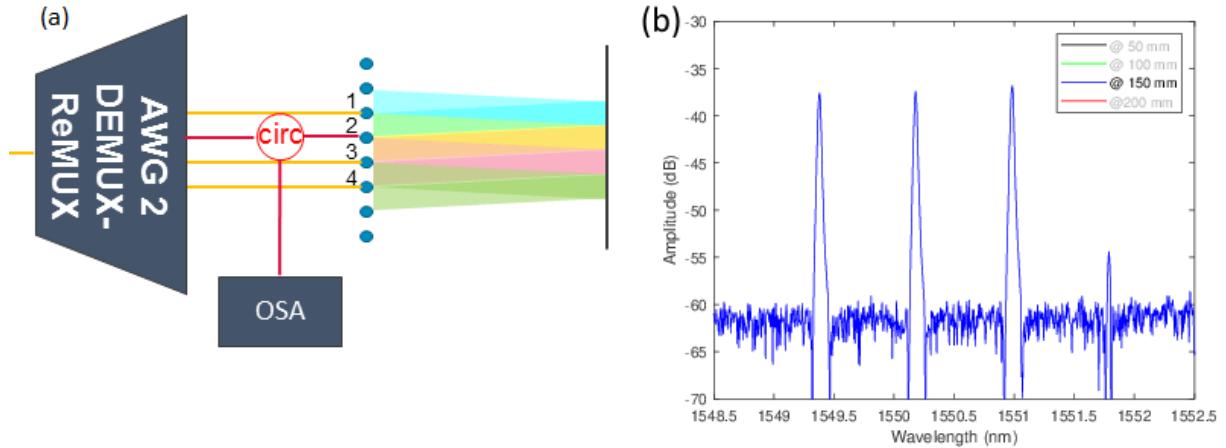
## CROSSTALK IN COLLIMATOR ARRAYS

In our ramp compression experiments, arrays and lines of collimators, already pre-aligned in the factory, are used. A very compact one is a line of 8 GRIN (gradient index micro-optic lens) collimators which are 0.5 mm in diameter and have a 1-mm pitch. Two of these lines of collimators can be connected to our multi-wavelength PDV system. A picture of a prototype of this line of 8 collimators is shown in Figure 1 (a). A first estimation of the crosstalk issue was completed by imaging. A smooth aluminum plate was used as a target with a 45° angle; its surface quality is representative of a HPP generator electrode. An image of the 8 beams has been taken 40 mm away from the aluminum plate which was itself 40 mm away from the line of collimators (top image of Figure 1 (b)). One can see that the first beam on the left is weaker as its fiber was damaged before the experiment. The other beams have about the same intensity. One can see that beams 2, 3 and 4 starts to overlap. If we move the NIR camera 35 mm further, the bottom image of Figure 1 (b) is obtained. At this distance, even after a reflection on a smooth surface, all the neighboring beams overlap. In order to quantify what is really coupled back into the single mode fiber (core diameter of ~9  $\mu\text{m}$ ), the following characterization was performed.



**FIGURE 1.** (a) Photography of a line of 8 collimators spaced (center-to-center) by 1 mm. (b) NIR images of the 8 beams (top) at a distance of 40 mm from a smooth aluminum plate 40 mm away from the collimators and (bottom) at a distance of 75 mm from the smooth aluminum plate which is still 40 mm away from the collimators.

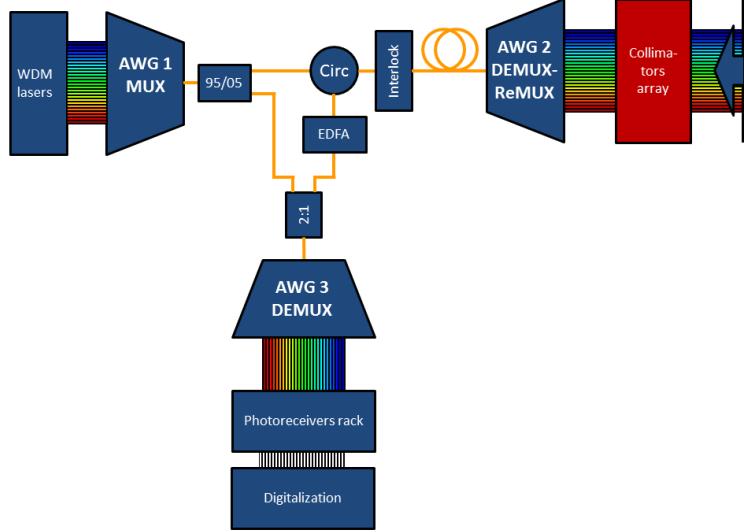
This second characterization is described in Figure 2 (a). Four lasers at different wavelengths were connected to four neighboring collimators. The reflected signal from the second collimator was routed to an Optical Spectrum Analyzer (OSA) by a circulator. If no crosstalk was present, only the 2<sup>nd</sup> wavelength should be visible in the OSA spectrum. Spectra were recorded with the aluminum plate at distances of: 50, 100, 150 and 200 mm. At 50 mm, no crosstalk (< 40 dB) was detected on the OSA. At 100 mm, the crosstalk level is in the order of -10 dB. At 150 mm, the crosstalk is already maximal as shown in the spectrum of Figure 2 (b). Crosstalk can be present in numerous experiments where the distance is significant and/or depending on the target surface diffusion.



**FIGURE 2.** (a) Crosstalk evaluation scheme. (b) Reflected spectra on collimator 2 for a smooth aluminum target at a distance of 150 mm; the pitch is 1 mm.

## MULTI-WAVELENGTH PDV SYSTEM

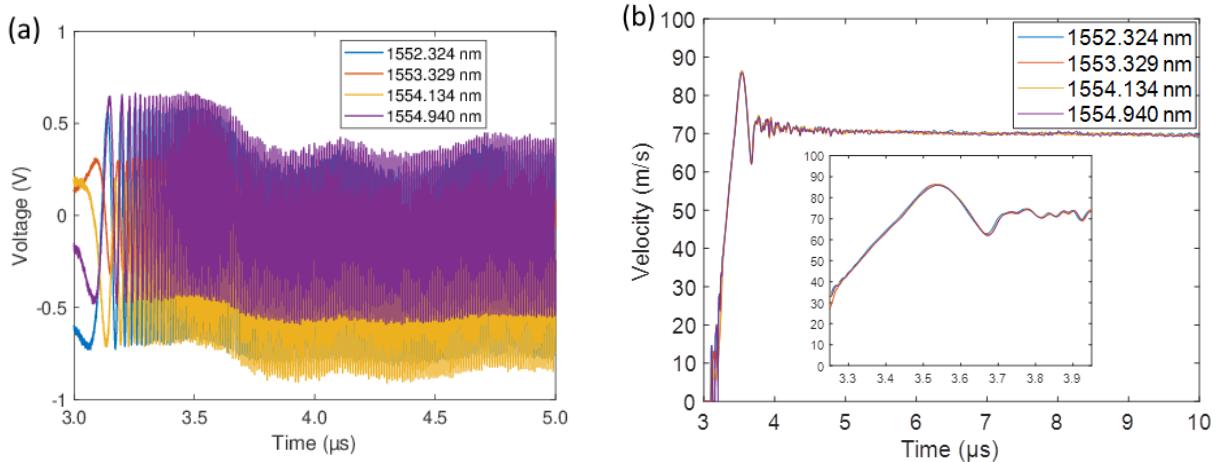
The scheme of our 16 wavelengths PDV system is presented in Figure 3. The individual wavelengths are generated by 4 cards of 4 lasers in a single rack normally used in Wavelength-Division Multiplexing (WDM) optical networks. Their linewidth and maximum output power are respectively 140 kHz and 34.5 mW. The 16 wavelengths are multiplexed by AWG 1. All AWGs are identical, have 100-GHz channels spacing and were designed to have “flat-top” channels<sup>19</sup>. The optical losses, including the input and output fiber coupling, are ~3.5 dB. Then, a fraction of the 16 wavelengths is collected by a 95:5 fiber coupler to create the interferometer reference arm. After the optical circulator, an interlock is inserted for laser safety just before exiting the optoelectronic rack. A single fiber, typically 20-50 m long, brings the 16 probe signals to AWG 2. This AWG, being close to the experiments (< 3 m), is mounted in an armored rack. AWG 2 demultiplexes the 16 wavelengths and is connected to a 16 collimators array or two lines of 8 collimators. The 16 Doppler signals are coupled back and remultiplexed by AWG 2. The reflected signals are amplified by an EDFA (Erbium-Doped Fiber Amplifier) located between the circulator and the 2x1 coupler. It compensates the optical losses (back and forward) of AWG 2 and equalizes the levels with the reference arm. The 2x1 coupler makes interfering the 16 Doppler signals with their respective references. Finally AWG 3 demultiplexes the interferences signals which are directly detected by 2-GHz bandwidth photoreceivers. The time multiplexing scheme developed and described in Ref. 13 could have been added to reduce the number of photoreceivers and digitizers, however it was not requested by the end users. The actual system could also be upgraded to measure high velocities by increasing the bandwidth of the photoreceivers and digitizers; the 100 GHz channel spacing of the AWGs is wide enough. If WDM and time-multiplexed<sup>13</sup> PDV systems do not decrease the bandwidth as frequency-multiplexed systems<sup>11,12</sup>, they however have additional optical losses. In the presented PDV system, only one EDFA is used for all wavelengths when a time-multiplexed system typically needs as many amplifiers as channels except for the first one which is not delayed.



**FIGURE 3.** Scheme of the 16 channels multi-wavelength PDV system.

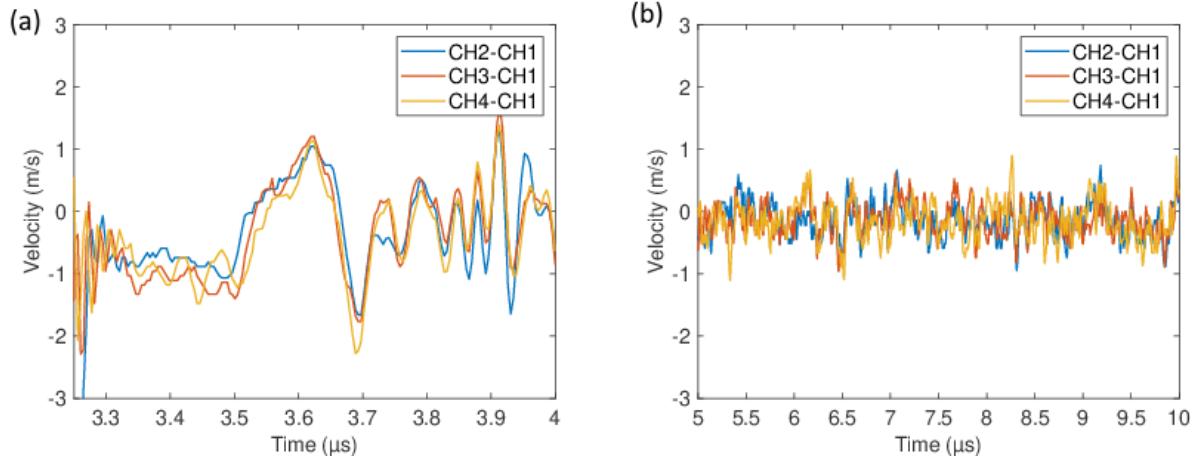
## RAMP COMPRESSION EXPERIMENTS

The system was initially tested with 8 consecutive wavelengths on a test bench at low velocity ( $< 1$  m/s) using the line of 8 collimators on the representative aluminum plate. With such test bench, the measurement time is much longer ( $\sim 500$  ms) than in ramp compression or shock physics experiments. On these long signals, small features in the velocity profiles can be observed, they are certainly due to the modest linewidth of the WDM lasers used. This is however much less critical in fast experiments. The real validation of the system was therefore done with our GEPI<sup>12</sup> HPP generator. AWG 2 was temporary by-passed so that all the wavelengths probe the same point on the studied material. This is the most challenging setup to evaluate possible crosstalk issues. The following result was generated with 4 wavelengths only because the 12 other lasers were unfortunately not available at that time. The raw data, from the ramp compression experiment, are shown in Figure 4 (a) for the two first  $\mu$ s. The 4 signals are truly four independent series of fringes. This dataset was processed by STFT and the four velocity profiles obtained are plotted in Figure 4 (b). A peak at  $\sim 86$  m/s is reached in 0.5  $\mu$ s and then there is a plateau at  $\sim 70$  m/s. The figure inset zooms on the peak and no difference can be seen between the 4 wavelengths.



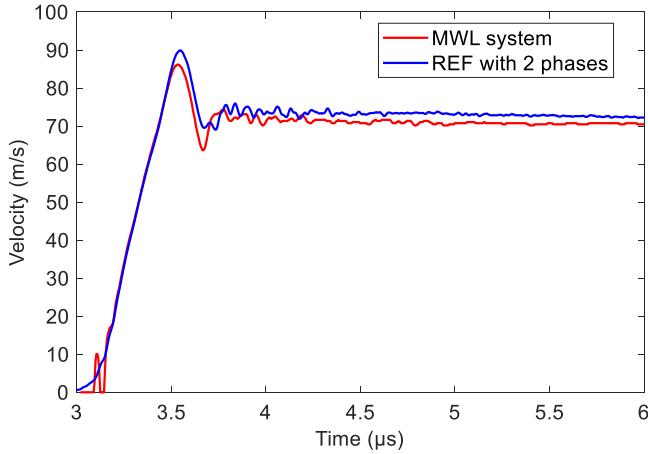
**FIGURE 4.** (a) Raw PDV data for the 4 wavelengths. (b) Velocities obtained from the raw data by STFT.

In order to evaluate the differences in the velocity profiles between the 4 wavelengths (Figure 4 (b)), channel 1 was set to be the reference velocity signal and the 3 other signals were subtracted. The differences in velocities obtained are plotted around the velocity peak between 3.25 and 4.00  $\mu$ s in Figure 6 (a) and for the plateau between 5.0 and 10.0  $\mu$ s in Figure 5 (b). Around the peak, the maximum differences are locally +1.7 m/s and -2.3 m/s. The standard deviations were calculated for these time ranges and values of only ~0.30 m/s were obtained. On the plateau, the maximum differences are locally  $\pm$  1.0 m/s. The standard deviations were also calculated and values of less than ~1.0 m/s were obtained. We can conclude that the system is performing excellently with maximum crosstalk, although we suspect that the modest linewidth of the WDM lasers used increases slightly the velocity uncertainties. Better WDM lasers are nowadays available on the market with linewidth lower than 10 kHz. Another way to compensate the linewidth influence is to minimize the optical length between the interferometer arms. In this experiment, the difference was about 46 m. An additional fiber can easily be inserted in the reference arm between the 95:5 coupler and the 2x1 coupler. The improvements will be soon characterized with the 16 wavelengths.

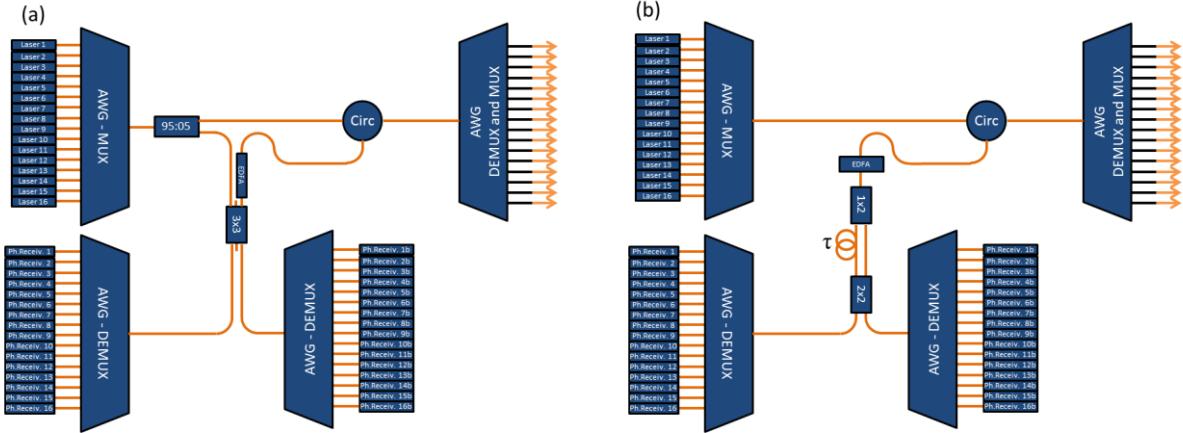


**FIGURE 5.** Differences in velocities using the first channel as reference (a) around the peak between 3.25 and 4  $\mu$ s and (b) on the plateau between 5 and 10  $\mu$ s.

One can notice that STFT didn't perform perfectly between 0 and 20 m/s in figure 4(b) due to the Heisenberg-Gabor theoretical limit. Better results can be obtained with wavelets<sup>20,21</sup>, but we usually use PDV systems which can process as well phases on 2 or 3 signals<sup>8-10</sup>. In the presented HPP experiment above, a reference velocity measurement with 2 phases was done in the center of the sample. The multi-wavelength probe was 12 mm away from the center. The velocity profiles comparison is plotted in Figure 6 and they are in very good agreement. The small differences are explained by the distance between the measurement points. The data processing with the 2 phases of the reference measurement allowed to get correctly the velocity profile between 0 and 20 m/s. WDM allows as well building a push-pull<sup>9-10</sup> system with phase analysis. This will certainly be one of the evolutions of our multi-wavelength system. Following the same approach, an all-fiber VISAR<sup>22,23</sup> with a common delay line can be built using WDM. These two schemes are given in Figure 7 (a) and (b) for illustration with again 16 wavelengths.



**FIGURE 6.** Comparison of velocities obtained by STFT with one wavelength of the new multi-wavelength PDV system and by 2 phases processing of our reference push-pull PDV system.



**FIGURE 7.** (a) Scheme of a 16 wavelengths Photonic Doppler Velocimetry (WDM push-pull PDV) with time-frequency or phase analysis and Displacement system (with phase analysis). (b) Scheme of a 16 wavelengths Velocity and Displacement system (WDM all-fiber VISAR) with phase analysis.

## CONCLUSION AND OUTLOOK

We presented a multi-wavelength crosstalk-free photonic Doppler velocimetry with 16 channels. The crosstalk issue was brought on a compact line of collimators with a pitch of 1 mm. The crosstalk certainly increases with surface diffusion and could invisibly disrupt PDV measurements performed at the same wavelength. The validation of the system was done on a HPP generator in a velocity range of [20-90] m/s. The setup was modified so that 4 wavelengths measure the same point on the target with maximum crosstalk. With 100 GHz spacing between the lasers frequencies and the WDM channels, the crosstalk was completely cancelled and didn't disrupt the velocity measurements. This channel spacing is suitable for higher velocity measurement (*i.e* 10 km/s). We identified that the WDM lasers used would need to be upgraded to reduce further the uncertainties on the velocities. WDM could be combined with time-multiplexing to reduce the number photoreceivers and digitizers even if that was not the aim of our system. WDM push-pull PDV and WDM all-fiber VISAR schemes were shortly introduced to improve the data processing of abrupt low velocity profiles. New experiments are being prepared to further evaluate an improved multi-wavelength system and using compact the presented compact lines of collimators.

## ACKNOWLEDGEMENT

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

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