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Measurement of the travel time in the upper Yellow River in 2015

Zhaodong Sun[1, 4], Yatong Zhang[2], Zhangyang Song[1], Hong Sun[1] and Yigong Sun[3]

[1] Yellow River Water Resources Protection Institute, Zhengzhou 450004, China
[2] Hydrology and Water Resources Bureau of the Ningxia-Inner Mongolia Reach, YRCC, Baotou, China
[3] Henan Province Qinghezhi Environmental Protection Science and Technology Company Ltd., Zhengzhou, China

[4] E-mail: sunzd2003@vip.sina.com

Abstract. The solute travel time in steady and gradually varied flow in rivers is necessary for waste transport studies, in particular, to evaluate the behavior of accidentally spilled soluble substances in streams. This study conducted two dye tests on the Donghe reach within Baotou in the upper Yellow River to measure the travel times in October 2015. It reconstructed the leading and trailing edge missed data by extension from time-concentration curves developed by fitting a three-parameter log-normal (3PLN) equation to the discretely observed data. It also calculated the travel times, dispersion rates, and longitudinal dispersion coefficients. The results show that the calculated travel rates of the centroid are less than the velocities at the Baotou hydrometric station. The calculated longitudinal dispersion rates ranged from about 0.22 meters per second to 0.68 meters per second. Using the nonlinear best fit method, a dispersion model for an instantaneous injection of tracer gave the longitudinal dispersion coefficients ranging from about 76 square meters per second to about 304 square meters per second. However, the ones generated by some commonly used empirical equations are at least 2.6 times them. Tracing tests are essential to obtain helpful information for pollutant transport studies.

1. Introduction

The Yellow River, located in the north of China, is the second largest River in China and is well known for its high concentration of suspended sediment worldwide. The Yellow River is a vital source of domestic, industrial, and agricultural water and the receiving body of sewage, wastewater, and agricultural return water. Baotou city, located in the upper Yellow River, discharges most of its sewage and wastewater through the two ditches of Erdaoshahe and Donghecao. There is a public drinking water source location of Dengkou 20 km downstream from the Erdaoshahe and Yellow River confluence. It is necessary to determine the allowable permitted assimilative capacity and develop an emergency response plan for water pollution incidents. It needs information about solute travel times in steady and gradually varied flow in streams to conduct waste transport studies, mainly to evaluate the behavior of soluble substances accidentally spilled in streams [1]. Tracing studies can provide such information. However, there were only several such studies conducted in the trunk stream of the Yellow River before 2015 [2-5]. Nevertheless, they focused on the dispersion coefficients rather than travel times, and their study reach length is less than 8000 m. Researchers usually did dye-tracer studies to enhance knowledge of transport characteristics, which include streamflow velocities, travel times, and dispersion rates, within a river system [6]. This study conducted two dye tracings in October 2015 for travel times in the Donghe reach of Baotou in the upper Yellow River.

When assessing the data completeness, we identified the incomplete trailing edge for the discharge of 928 m^3 s^{-1} and the incomplete leading edge for the discharge of 316 m^3 s^{-1}. How to estimate the missing data? It takes work. An inappropriate method will generate an inappropriate time-concentration curve. Researchers used a three-parameter log-normal (3PLN) equation to fit the observed data of travel time tracing studies [7-8]. A comparison of the accuracy of the best fit between measured and modeled data using different approximation methods showed that the three-parametric log-normal distribution approximation method is more precise than Gumbel and Gauss methods [9]. We will use a 3PLN equation to fit the observed data best to reconstruct the missing data of five ones in the six groups observed data in October 2015. Another tracing study [8], in which observed data is of good quality, was conducted in the upper Yellow River in May 2017 based on the experience obtained in 2015.

2. Materials and methods

2.1. Hydraulic parameters of the Yellow River at Baotou station

October is the last month of the flooding season of the Yellow River. The low flow will follow the high flow. Selecting this time to conduct the tracing studies is possible to obtain the travel times for both high flow and low flow. The study is between the Wandahan floating bridge and the Dengkou water quality monitoring section. Its channel length is 31288.9 m, sinuosity is 1.70, and the average channel slope is 0.000089, recorded in a red book of Yellow River Basin Characteristics compiled by YRCC in 1977 or 0.00010 shown in an article [10]. A plan for the study is in Figure 1. The Baotou hydrometric station is 7.7 km upstream of the Wangdahan floating bridge. When pouring Red acid 52, the hydraulic parameters of the Yellow River at Baotou station are in Table 1. The suspended sediment concentrations are 5.55 kgm^{-3} and 1.13 kgm^{-3} for the two dye studies. The two ditches of Erdaoshahe and Donghecao discharged sewage and wastewater of 2.88 m^3s^{-1} into the River within the Donghe reach in October 2015.

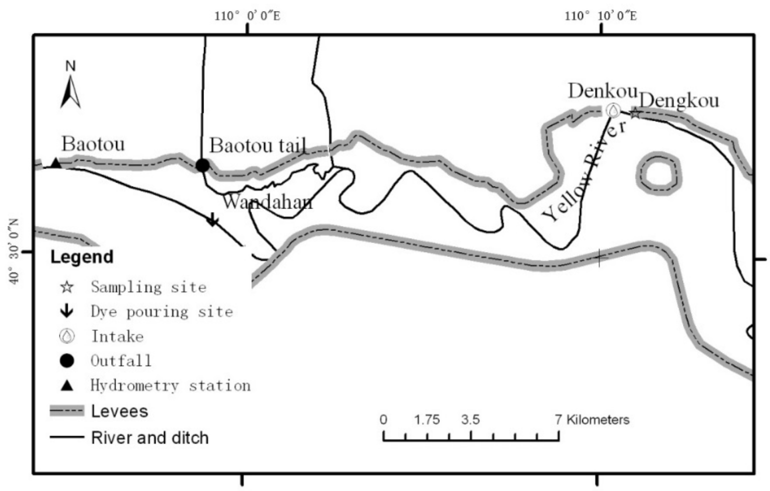

Figure 1. Plan of study reach.

Table 1. Hydraulic parameters of the Yellow River at Baotou station.

No.	Date	Time	Water level (m)	Discharge Q (m^3s^{-1})	Cross-section Area A(m^2)	Velocity U (ms^{-1})	Width B (m)	Depth H (m)
1	Oct 18,2015	10:12	1002.91	928	647	1.435	294	2.20
2	Oct 21,2015	22:03	1002.25	316	425	0.744	228	1.86

Note: Modified from the discharge measurement result table of the Baotou station of YRCC in Oct 2015.

2.2. Dye

Using fluorescent dyes and tracing techniques measures the time of travel of solutes in steady and gradually varied flow in streams [1]. The Rhodamine group is suspected to be toxic, except for Amidorhodamine G and Sulforhodamine B (Acid red 52), which are less problematic [11]. So, acid red 52 (CAS: 3520-42-1) of the technical grade was selected as a tracer to measure the travel time in our study.

2.3. Methods

2.3.1. Dye dissolution and injection. The Yellow River discharge was 928 m^3s^{-1} for the first dye test at the Baotou hydrometric station. We divided 16 kg powder of acid red 52 into eight equal parts, 2 kg per part, and put each part into a bucket. We added the Yellow River water into the eight buckets and stirred well to dissolve the powder on-site fully. The dye solution was poured into Yellow River, facing downstream, in about central two-thirds of flow, simultaneously at 11:04 on 18 October 2015 at 8 points from the Wandahan floating bridge. We located each injection point at the approximate flow center of each of the eight equal discharge segments according to hydrometric experience.

The Yellow River discharge is 316 m^3s^{-1} for the second dye test at the Baotou hydrometric station. We divided 7 kg powder of acid red 52 into seven equal parts, 1 kg per part, and put each part into a bucket. We added the Yellow River water into the seven buckets and stirred well to dissolve the powder on-site fully. The dye solution was poured into Yellow River, facing downstream, in about central two-thirds of flow, simultaneously at 22:03 on 21 October 2015 at 7 points from the Wandahan floating bridge. We located each injection point at the approximate flow center of each seven equal discharge segments according to hydrometric experience.

2.3.2. Sample collection. On boats, we collected water samples at the left bank (2 m from the water's edge), midstream, and right bank (2 m from the water's edge). The Yellow River water at 0.2 m or more depth below the water surface was pumped continuously by mini submersible pumps. The water sample was collected and sealed into a glass bottle of 100 ml once every 5 minutes or 10 minutes. We sent the water samples to a laboratory for a static settlement of about 10 hr.

For the first dye study, water sample collection began at 15:30 on 18 October 2015 and ended at 18:27 on 18 October 2015.

For the second dye study, water sample collection began at 11:57 on 22 October 2015 and ended at 20:07 on 22 October 2015.

2.3.3. Dye concentration measurement. In the laboratory, the dye concentration in the clear supernatant liquid after a settlement is reported and observed using Turner Designs Fluorometer 10-005. The air temperature in the laboratory was stable thanks to a central heating system. This study prepared a standard regent of 10 μgL^{-1} using deionized water to dissolve the powder of acid red 52, calculated the readouts of unknowns and standards following the user's manual, and calculated the measured concentration from the readouts of unknowns and standards. The observed concentration is calculated by subtracting the background value measured at the Wandahan floating bridge on June 26, 2017, for the discharge of 233 m^3s^{-1} [8] and measured at the Dengkou cross-section in this study for the discharge of 928 m^3s^{-1}.

2.3.4. Data processing. (1) Estimation of missing data. This study reconstructed the leading and trailing edge missed data by extension [1]. A fitted observed time-concentration response curve makes the extension.

This study used a 3PLN Equation (1) to fit the resulting data to establish a fitted observed time-concentration response curve:

$$C(x,t) = \frac{A_{cr}}{\sqrt{2\pi}(t - t_{x,0})\sigma_x} \exp\left[-\frac{1}{2} \left(\frac{\ln(t - t_{x,0}) - \mu_x}{\sigma_x} \right)^2 \right] \tag{1}$$

where $C(x,t)$ is the dye concentration (μgL^{-1}) at distance x; t is elapsed time after injection in hours; A_{cr} is the area under the time-concentration curve (μgL^{-1} hours); μ_x, $t_{x,0}$, and σ_x are parameters.

Theoretically, $A_{cr} = \frac{w_r}{Q} \times \frac{1}{3600} \times 10^6 \approx 277.78 \times \frac{w_r}{Q}$. Where Q is the discharge (m^{3}s^{-1}) at the sampling cross-section; W_r is the weight of tracer recovered.

(2) Percent recovery

We calculated the percent recovery using the parameter w_r of the fitted observed time-concentration response curve as

$$R_p = \frac{w_r}{w} \times 100 \tag{2}$$

where R_p is percent recovery; w is the total quantity of dye injected.

For steady and gradually varied flow, $w_r = Q\int_{T_e}^{T_f} C_0 dt = QA_{cr}$ [12]. Where the integral is the area, A_{cr}, of the observed tracer response curve from the time of the leading edge, T_e, to the time of the trailing edge, T_f.

2.3.5. Travel time and dispersion rate. The dispersion time can be obtained from the fitted time-concentration response curve. The dispersion times of the dye plume include:

T_l is the leading edge travel time in hours;

T_p is the peak concentration travel time in hours;

T_{10pt} is the trailing edge travel time where dye concentration is reduced to 10 percent of the peak concentration in hours;

T_t is the trailing edge travel time in hours;

T_d is the time necessary for the dye plume to completely pass a measurement site in a section, which equals to $T_t - T_l$; and

T_c is the centroid travel time in hours [12].

T_c can be calculated by using Equation (3) [13]:

$$T_c = t_{x,0} + \exp(\mu_x + \frac{(\sigma_x^2)}{2}) \tag{3}$$

where $t_{x,0}$, μ_x, and σ_x are the parameters of the 3PLN equation.

This study estimated the longitudinal dispersion rate for the Donghe reach, subtracting the velocity of the trailing edge from the velocity of the leading edge [7].

$$R_{ld} = \frac{1000L}{3600T_l} - \frac{1000L}{3600T_t} \tag{4}$$

where R_{ld} is the dispersion rate (ms^{-1}); L is reach length (km). Because longitudinal dispersion, having no boundaries, continues indefinitely [1], the trailing edge missing data was estimated from the fitted time-concentration curve. It took T_{10pt} as T_t.

2.3.6. Longitudinal dispersion coefficient. This study calculated the longitudinal dispersion coefficients using a nonlinear curve fit method in the software of OriginPro 2018. For an instantaneous injection of tracer, a dispersion model presented in the Literature [14] was used to fit the data of percentage recovery adjusted concentration:

$$C(x,t)=\frac{w\times10^6}{A}\frac{1}{\sqrt{4\pi D_L(t\times3600)}}\exp\left[-\frac{(x-\bar{v}(t\times3600))^2}{4D_L(t\times3600)}\right]$$
$$=\frac{w\times10^6}{Q}\frac{\bar{v}}{\sqrt{4\pi D_L(t\times3600)}}\exp\left[-\frac{(x-\bar{v}(t\times3600))^2}{4D_L(t\times3600)}\right] \quad (5)$$

where $C(x,t)$ is percentage recovery adjusted concentration (μgL^{-1}); A is the area of sampling cross-section (m^2); Q is the discharge at sampling cross-section (m^{3}s^{-1}); w is the total quantity of dye injected (kg); x is the distance from injection cross-section (m); t is the elapsed time after injection in hours; D_L is the longitudinal dispersion coefficient in (m^{2}s^{-1}); $\bar{v}$ is the mean stream velocity (ms^{-1}).

3. Results

The observed data and fitted time-concentration curves are in Figure 2 and Figure 3. The missing data of the leading and trailing edge were estimated using the fitted curves.

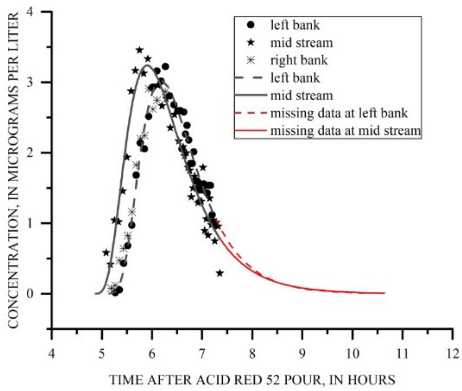

Figure 2. Observed data and their fitted time-concentration curves at the discharge of 931 m^{3}s^{-1}.

At the discharges of 928 and 316 m^{3}s^{-1} at the Baotou hydrometric station, this study calculated the travel times, travel rates, dispersion rates, and longitudinal dispersion coefficient for the reach between Wandahan and Dengkou in the upper Yellow River. It used the fitted time-concentration curve developed from data observed from two tracer studies in October 2015. It calculated travel rates for the leading edge, peak concentration, centroid, and trailing edge at 10 percent of the peak concentration of the dye plume. The centroid travel rate most accurately represents the mean streamflow velocity of the study reach, and the travel rates of the other portions suggest the possible rates of the dispersion of contaminants spilled into the study reach.

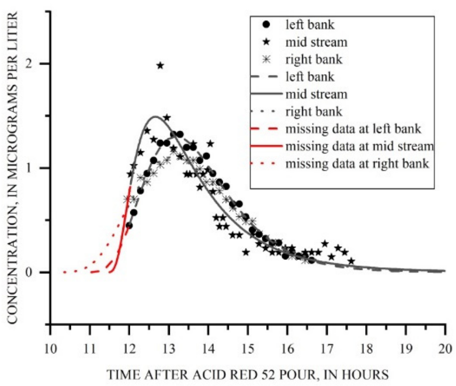

Figure 3. Observed data and their fitted time-concentration curves at the discharge of 319 m^{3}s^{-1}.

For the discharge of 931 m^3s^{-1} at the Dengkou cross-section, the centroid travel rates ranged from 1.319 to 1.363 ms^{-1}. The dispersion rates ranged from 0.599 to 0.677 ms^{-1}, and the longitudinal dispersion coefficients were from 234 to 304 m^2s^{-1}. The results of the first study are in Table 2.

Table 2. Travel times and dispersion characteristics at discharge of 931 m^3s^{-1}.

Locations	Left bank	Midstream	Right bank
Leading edge travel times (hr)	5.200	4.927	
Leading edge travel rate (ms^{-1})	1.671	1.764	
Peak concentration travel times (hr)	6.178	5.903	
Peak concentration travel rate (ms^{-1})	1.407	1.472	
Trailing edge travel times (hr)	8.104	7.996	
Trailing edge travel rate (ms^{-1})	1.072	1.087	
Centroid travel times (hr)	6.590	6.375	
Centroid travel rate (ms^{-1})	1.319	1.363	
Dispersion rates (ms^{-1})	0.599	0.677	
Longitudinal dispersion coefficients (m^2s^{-1}) for Equation (5)	234	304	
Percent recovery	94.8%	107.3%	
RMSE for 3PLN equation	0.156	0.221	
Adj. R-Square for 3PLN equation	0.95885	0.92659	
Adj. R-Square for dispersion model of Equation (5)	0.87541	0.85275	

Note: Travel time is time after injection, hr.

For the discharge of 319 m^3s^{-1} at the Dengkou cross-section, the centroid travel rates ranged from 0.632 to 0.635 ms^{-1}. The dispersion rates ranged from 0.221 to 0.314 ms^{-1}, and the longitudinal dispersion coefficients were from 76 to 103.5 m^2s^{-1}. The results of the second study are in Table 3.

Table 3. Travel times and dispersion characteristics at discharge of 319 m^3s^{-1}.

Locations	Left bank	Midstream	Right bank
Leading edge travel times (hr)	11.082	11.518	10.453
Leading edge travel rate (ms^{-1})	0.784	0.755	0.831
Peak concentration travel times (hr)	13.179	12.660	13.087
Peak concentration travel rate (ms^{-1})	0.659	0.687	0.664
Trailing edge travel times (hr)	16.449	16.292	16.811
Trailing edge travel rate (ms^{-1})	0.528	0.533	0.517
Centroid travel times (hr)	13.758	13.685	13.687
Centroid travel rate (ms^{-1})	0.632	0.635	0.635
Dispersion rates (ms^{-1})	0.256	0.221	0.314
Longitudinal dispersion coefficients (m^2s^{-1}) for Equation (5)	76	98	103.5
Percent recovery	58.7%	59.9	58.7%
RMSE for 3PLN equation	0.034	0.157	0.043
Adj. R-Square for 3PLN equation	0.99233	0.88054	0.98722
Adj. R-Square for dispersion model of Equation (5)	0.91287	0.73839	0.92789

4. Discussion

4.1. Selection of tracer

The Yellow River is known for its high concentration of suspended sediment. In the past, researchers did not select the dyes as tracers for Yellow River. The tracing studies from 1986 to 1991 selected dichromate, sodium dichromate, and Iodine 131 as tracers [2-4]. In the tracing studies of Shao [2], the maximum measured concentration of dichromate was 58.1 μgL^{-1}. In the tracing studies of Hu [3], the maximum measured concentration of sodium dichromate was 520 μgL^{-1}. However, the recommended freshwater CMC of Chromium VI by USEPA is 16 μgL^{-1} [15]. A high concentration of dichromate would impact the aquatic organisms.

During the tracing study in 2015, the suspended sediment concentrations ranged from 5.55 to 1.13 kgm^{-3}. Acid red 52 can be used as a dye tracer to conduct travel time studies in the upper Yellow River. Because the acid red 52 is water soluble, highly detectable, inexpensive, and reasonably stable in a typical water environment as recommended by USGS standard method [16]. This study measured the dye concentration in situ. However, the observed data in situ can only be used as a trend indicator for water sampling because the measured results would be affected by many factors, such as temperature and sediment concentration. It used the data observed in the laboratory as the standard to compute the travel times and dispersion characteristics of the study reach. Moreover, the background deduction would affect the computation result, and the background samples should be collected in advance.

4.2. Estimation of missing data
Kilpatrick and Wilson noted that sampling should begin early enough to catch the dye cloud's leading edge [1]. However, an imperfect design scheme and site environment change will lead to missing some data. For example, this study produced missing data at the leading and trailing edges. Especially on October 18, 2015, the right bank collapse stopped the sampling, leading to too much missing data on the trailing edge. The extrapolations of the leading and trailing edges will cause some uncertainty and are relatively time-consuming. We used the fitted curve obtained using a 3PLN equation to fit the observed data to reconstruct the leading edge missed data and the trailing edge missed data. The method is rapid and time-saving. In the two dye tracings, the Adj. R-Squares for the 3PLN equation are more significant than 0.88, showing that the equation best fits the data. Compared with the results of the tracing study conducted in May 2017, for the left bank of the Dengkou cross-section, the dispersion rate of 0.26 ms^{-1} at the discharge of 316 m^3s^{-1} on October 21, 2015, is equal to the one of 0.25 ms^{-1} (31496.2×(1/10.7773-1/15.7181)/3600) at the discharge of 233 m^3s^{-1} on May 26, 2017 [8]. It shows that the method is technically feasible for the data sets in which missing data is not too much.

4.3. Travel time or mean velocity of the study reach
Solute transport prediction and water environment capacity calculation need travel times. Researchers usually used the velocity of the nearby hydrometric station to do such work. However, a hydrometric station is always located in a straight section to measure the discharge conveniently and accurately. For a meandering stream, the depth, width, slope, and direction of flow change greatly downstream, and the velocity at one station cannot represent the average velocity for a reach. In general, the mean velocity for the study reach is less than that at the Baotou hydrometric station. Though the hydrometric measurement can give the mean velocities of water flow at different cross-sections of a reach, the tracing study can give the travel times and the mean velocities for the different parts of the time-concentration curve of dissolved pollutants for the entire reach. Researchers can use the centroid travel times to compute the water environment capacity and other travel times to estimate the arrival time of the different parts of the time-concentration curve for a water pollution accident.

4.4. Dispersion rate and longitudinal dispersion coefficient
Researchers used the dispersion rate to estimate the pollution length and the longitudinal dispersion coefficient in a water quality model. Researchers developed many empirical equations to estimate the longitudinal dispersion coefficient for natural rivers [17-20]. We listed some commonly used empirical equations for predicting longitudinal dispersion coefficients in Table 4 and the coefficients predicted by using the equations in Table 5. We can see that they are at least 2.6 times the ones listed in Table 2 and Table 3. None of them can give accurate ones for the discharges, both 316 and 928 m^3s^{-1} at Baotou hydrometric station in the upper Yellow River.

Table 4. Some commonly used empirical equations predicting longitudinal dispersion coefficient.

No.	Empirical equations
EF(1)	$D_L = 0.011U^2B^2/(Hu_*)$ [17]
EF(2)	$D_L = 5.915(U/u_*)^{1.428}(B/H)^{0.620}Hu_*$ [18]
EF(3)	$D_L = 10.612HU(U/u_*)$ [19]
EF(4)	$D_L = \left[7.428+1.775(B/H)^{0.620}(u_*/U)^{0.572}\right]HU(U/u_*)$ [19]
EF(5)	$D_L = 5.4(B/H)^{0.7}(U/u_*)^{0.13}HU$ [20]

Table 5. Longitudinal dispersion coefficient predicted by using different equations.

No.	Discharge Q (m^3s^{-1})	Velocity U (ms^{-1})	Width B (m)	Depth H (m)	Slope (%)	Shear elocity u_* (ms^{-1})	Longitudinal dispersion coefficient D_L				
							EF(1)	EF(2)	EF(3)	EF(4)	EF(5)
1	928	1.435	294	2.2	0.0089	0.044	20310	1729	1097	1287	826
2	316	0.744	228	1.86	0.0089	0.0404	4220	562	271	358	316

5. Conclusions

Acid red 52 can be selected as a dye tracer to conduct dye studies in the upper Yellow River, at least under the suspended sediment concentration of fewer than 5.55 kgm^{-3}. Collecting the background samples at the sampling cross-section in advance is essential because the background value deduction will affect the computation results. The water sampling should begin as early as possible to avoid the leading-edge missing data, and the sampling duration should last longer to prevent the trailing-edge missing data. This study reconstructed the leading and trailing edge missing data using a fitted time-concentration curve. We develop the curve using a 3PLN equation to fit the observed data. Researchers can use the centroid travel times to compute the water environment capacity and other travel times to estimate the arrival time of the different parts of the time-concentration curve for a water pollution accident. For the study reach, the calculated velocities for the centroid of the dye plume are more significant than the ones at the Baotou hydrometric station, and the dispersion rates and longitudinal dispersion coefficients at the high flow period are greater than at the low flow period. Researchers use the dispersion rate to estimate the pollution length and the longitudinal dispersion coefficient in a water quality model. They developed many empirical equations to predict the longitudinal dispersion coefficients for natural rivers. However, the empirical equations needed to give accurate ones for the discharges of 316 and 928 m^3s^{-1} at the Baotou hydrometric station in the upper Yellow River. So, tracing tests are essential to obtain helpful information for pollutant transport studies.

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Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data is not available.

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