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Validity and Reliability of an on-bike sensor system for the determination of aerodynamic drag in cycling

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ABSTRACT

Objectives: Cycling performance is strongly influenced by aerodynamics, with most resistive drag forces being attributed to the rider. Optimising aerodynamic position from accurately and reliably measuring aerodynamic resistance (CdA) is therefore in the interests of all competitive cyclists. The Body Rocket device (BR) is an on-bike sensor system that uses the same load cell technology as a wind tunnel, directly measuring real-time CdA from the rider. This study aimed to measure the validity and reliability of CdA measures from BR in two experiments. *Design:* Experiment 1, validity of BR was assessed in wind tunnel with a rod and discs of known diameter attached to the end change CdA by a known amount. Experiment 2, validity and reliability of BR was assessed in an indoor velodrome. *Methods:* Ten cyclists performed 7 identical efforts at ~40km/h for 10 laps of the velodrome, the first 4 to assess validity with the same rod and discs used in the wind tunnel, with the remaining 3 without changes in resistance or the riders changing position to assess reliability. Results: Validity results demonstrated BR measured CdA to be strongly correlated with calculated CdA from the disc addition (r^2 = 0.99), with the smallest identified changes being 0.002m^2 across wind tunnel and velodrome. A high level of reliability was demonstrated during experiment 2 with strong intra-class correlation (0.99) and small coefficient of variation (1.67%). *Conclusions:* Findings of this study demonstrate BR is a valid and reliable device for measuring real-time CdA during cycling in an indoor velodrome.

Keywords Coefficient drag, Performance, wind tunnel, time trial, testing

INTRODUCTION

Cycling speed is determined by a rider's power output, road surface, environmental conditions, and aerodynamic drag (CdA). The importance of aerodynamics to performance in cycling is well documented with drag forces contributing approximately 90% of resistive forces when riding at speeds above 50 km/h [1-3]. Whilst the bicycle provides a source of drag, the majority can be attributed to the rider, therefore it is important to reduce or minimise drag to improve performance. Indeed, previous research has demonstrated that a 16.7% reduction in drag forces can be experienced between riding on the hoods compared to a crouched position using aerobars [4]. To put this in context, the reduction in drag force is estimated to result in a reduction of 70.1W whilst maintaining a constant cycling velocity of 45 km/h.

The gold standard approach to measuring aerodynamic drag is to use a force balance within a wind tunnel, which has been shown to produce highly precise and repeatable conditions [5], but the high cost associated with testing makes it prohibitive for most. The wind tunnel also creates an artificial environment unlike the conditions a rider would experience if riding outside and therefore may not truly reflect race conditions which is influenced by factors such as wind speed, road conditions, fatigue etc.... Similarly other approaches for estimating CdA, such as the use of mathematical models using measured power output and speed of riders [6], dynamometric methods [7], coasting-down and deceleration methods [2], and digitalisation or weighing photographs [8] do not provide a direct measure of drag and, similarly to the wind tunnel, do not reflect real-world cycling [9].

An alternative approach is for riders to use an indoor velodrome that allows for controlled environmental conditions, a cycling power meter and, an aerodynamic sensor attached to the bicycle to provide an estimation of CdA during cycling. Indeed, various commercially available systems (such as Aerosensor or Notio Aerometer) exist for estimating CdA which consist of a pitot tube for collection of air pressure, humidity and temperature, as well as a gyroscope or accelerometer. When combined with a power meter for measuring power output and ground speed, it is then possible for these systems to indirectly compute CdA. Previous research has shown such systems to produce data which is comparable to mathematical models, and capable of reliably detecting positional changes in CdA [10-14]. However, as outlined above, indirect drag force systems have various assumptions associated with drive train losses, rolling resistance, and weight changes relying on a technique often referred to as 'Virtual Elevation' [15].

Recently, an on-bike sensor system (Body Rocket Ltd, Sussex, UK) has been developed to directly measure the real-time aerodynamic drag of a rider. The system utilises 4 force sensors; one on the handlebar, one on the saddle and one on each pedal (see Figure 1). As each of these sensors are at the contact points of the bike, the drag of the rider can be determined through measuring the horizontal force at the sensor. The system also measures moments on the saddle and handlebar.

These sensors simultaneously measure forces applied in the horizontal and vertical planes, including 'roll' and 'pitch' moments, as well as the inclination of each sensor relative to the bike frame. Where the rider is stationary, the sum of the horizontal forces on the four sensors therefore summates to zero, with the sum of the vertical forces relative to the ground being equivalent to the weight of the rider. When the rider travels forwards through the air, the aerodynamic drag is determined by the Body Rocket system as the sensor arrangement isolates the rider from the bike at all contact points. Therefore, using the same approach as the wind tunnel, the measurements of aerodynamic drag recorded by the system only represent those of the rider. However, no previous study has assessed the reliability, validity and sensitivity of the Body Rocket system to measure CdA in static wind tunnel and free cycling conditions. Therefore, the aim of this study was to assess the reliability of Body Rocket during cycling as well as its validity and sensitivity to detect changes in CdA in both wind tunnel and velodrome environments.

METHOD

This study comprised of two experiments to assess the validity and reliability of the Body Rocket system to measure aerodynamic drag. In the first experiment a wind tunnel was used to determine the accuracy and sensitivity of the Body Rocket system. In experiment 2, ten competitive male cyclists completed 8 runs of 10 laps of a 250m indoor velodrome at a constant speed to determine the validity and sensitivity, as well as the reliability of the Body Rocket. The study and its methods were approved in agreement with the Declaration of Helsinki by the Research Ethics Committee of the University of Kent (Ref: 07_20_22).

Experiment 1

To determine the validity and minimal change in CdA that can be measured by the Body Rocket system a known amount of drag was added to a bike in a wind tunnel environment (SSE, Silverstone, UK). Drag was added using a series of disc plates of increasing sizes (50, 60, 80 and 100 mm) attached to the handlebars of the bicycle by a 1-metre-long rod. The drag of each disc was calculated using a theoretical first principles approach [16] and measured via Body Rocket in the wind tunnel at a wind speed of 11.5 m/s or 41.4 km/h. Drag increments between disc sizes were used to compare changes in CdA between the theorical value and that measured by Body Rocket to ascertain validity and sensitivity of the system in the wind tunnel. CdA values were obtained from 30 second recordings with a rider holding an aerodynamic position on the bicycle (see figure 1b) and of the bike-disc combination without a rider.

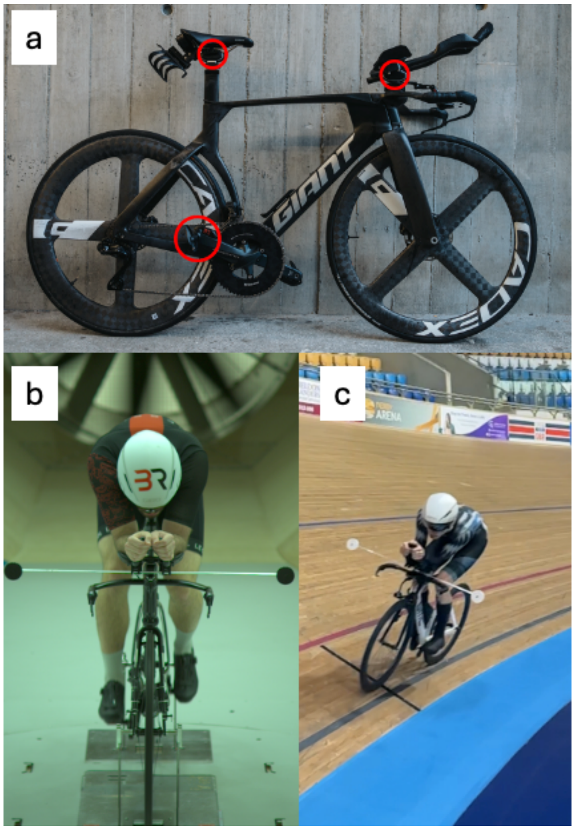

Figure 1: a) A bicycle with the Body Rocket system mounted, force sensors shown circles in red located at the main points of contact for the rider on the bicycle; b) Set-up used for Wind Tunnel Testing with rider on bicycle; c) A rider performing a velodrome run with rod and discs attached.

Experiment 2

Ten male cyclists volunteered to take part in this study, all having velodrome riding experience prior to participating in the study. All participants provided written informed consent after having the procedures explained to them both verbally and in writing.

The study took place in an oval 250m indoor velodrome (Derby, UK) with environmental conditions being kept consistent throughout to minimise environmental influences (e.g. one rider on a track at a time) with average environmental conditions being 20°C, 77.9% humidity, 998kPa. Participants used an instruments bicycle adjusted for their body dimensions. Each cyclist completed a total of 8 runs of 10 laps holding a time trial position, three performed to establish the reliability, and four runs with a disc plate of 50, 60, 80 and 100 mm (see Figure 1). Cyclists first performed the 8 runs of the velodrome in the following order: warm-up, Reliability 1, 50mm disc, 60mm disc, reliability 2, 80mm disc, 100mm disc, reliability 3. Drag increments between disc sizes were used to ascertain the expected changes in riders' CdA measurements compared to the Body Rocket system. During the laps, riders were asked to ride the black line at the bottom of the track and hold a set speed by matching a 22 second lap time (11.5 m/s or 41km/h) to minimise unnecessary accelerations or decelerations, with real-time lap splits communicated by a track-side researcher. The first two laps of each run were used as build-up laps to reach the target lap time with the subsequent 8 laps being used for measurement. Riders had access to real-time speed, power and cadence data provided by a handlebar mounted computer.

Statistical analysis

Data were assessed for normality of distribution and heteroscedasticity. The relationship and 95% limits of agreement (LoA) between the Body Rocket measured change in CdA and theoretical change calculated between the various disc sizes was analysed with Pearson's correlation coefficients, with r-values of 0.1, 0.3, 0.5, 0.7 and 0.9 considered as small, moderate, strong, very strong and extremely strong relationships, respectively [17]. The 95 % limits of agreement (LoA) are presented as bias ± 1.96*SD, all other data are presented as mean ± SD unless otherwise stated. The alpha level for statistical significance was set a 0.05.

Differences in speed between the different velodrome runs were assessed using repeated measures ANOVA. To assess reliability of the Body Rocket system, the within-subject variation, expressed as a typical error, coefficient of variation (CV) and intra-class correlation coefficient, was derived from CdA data collected during the 3 repeated velodrome runs without discs attached to the rod. ICC values were interpreted as: low, <0.80, moderate, 0.80-0.90, high, >0.90. Standardised typical errors were interpreted using modified effect size thresholds of (trivial, ≤ 0.2; small, > 0.2–0.6; moderate, > 0.6–1.2; large, > 1.2 [18].

Results

Experiment 1

There was a strong, near perfect correlation between theoretical changes in CdA between disc sizes and those measured by Body Rocket within the Wind Tunnel (r^2 = 0.99; see Figure 2). The wind tunnel comparison between the theoretical CdA calculations and those measured by the Body Rocket system demonstrated an average difference across all disc sizes of 0.002 $\pm$ 0.005 m^2.

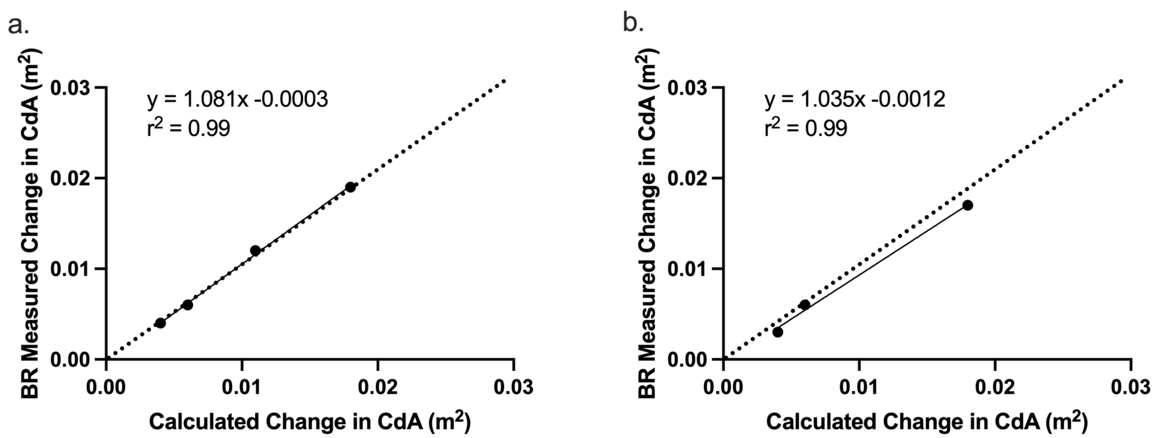

Figure 2: a. Relationship between theoretical and Body Rocket measured change in CdA with increasing disc sizes in Wind Tunnel. b. Relationship between theoretical and Body Rocket measured change in CdA with rider and increasing disc sizes in Wind Tunnel. 80mm disc size omitted due to excessive rider movement during data collection. Each black dot indicates a CdA value of a disc with increasing size from 50-100mm. Dotted line represents line of identity.

Experiment 2

Participants rode at a mean speed 41.4 ± 0.54 km/h (11.5 ± 0.15 m/s) during the 8 runs of the velodrome. There were no significant differences between the speeds on either the reliability runs ($p = 0.39$) or the disc test runs ($p = 0.32$). The relationship between the theoretical and Body Rocket measured changes in CdA from the different disc sizes demonstrated a large positive relationship ($r^2 = 0.99$, Figure 3a). The relationship between Body Rocket measured wind tunnel (with rider) and velodrome changes showed a similarly large relationship (r2 = 0.99, Figure 3b).

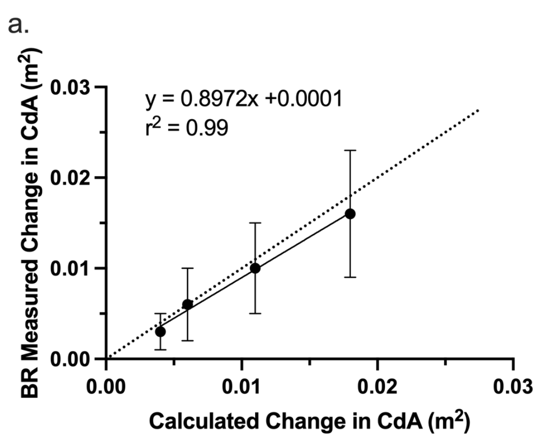

Figure 3a. Theoretical calculated changes in CdA vs. Body Rocket measured velodrome changes in CdA with increasing disc size. 3b. Body Rocket measured Wind Tunnel changes in CdA vs Body Rocket measured velodrome changes in CdA with increasing disc size. 80mm disc size omitted due to excessive rider movement during Wind Tunnel data collection. Data represent mean ± SD of rider cohort. Each black dot indicates a CdA value of a disc with increasing size from 50-100mm. Dotted line shows line of identity.

Figure 4 shows the agreement between the theoretical and Body Rocket measured changes in CdA with increasing disc sizes, with the calculated 95% LOA of -0.012 to 0.009 m^2.

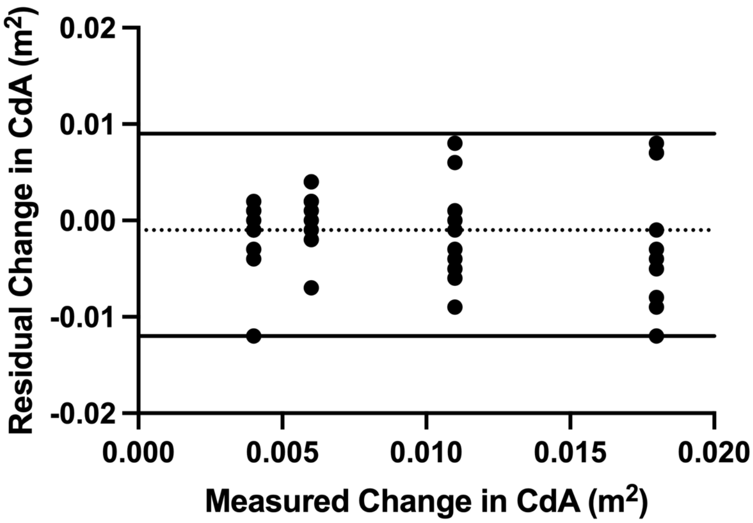

Figure 4. Bland-Altman plot of the difference between the theoretical and Body Rocket measured changes in CdA with increasing disc sizes during velodrome cycling. Dashed line represents the mean bias (-0.001 m^2) and solid lines are the 95% limits of agreement.

The mean CdA measured with Body Rocket during the three reliability velodrome runs across participants was 0.208 $\pm$ 0.03 m^2. Data was deemed to be reliable with absolute typical error being 0.004 (0.003 to 0.005) m^2 and standardised typical error 0.11 (0.08 to 0.13), suggesting a trivial between run effect. When expressed as a CV the typical error was 1.67% (90% CI = 1.20 to 2.86%) and ICC = 0.99 (90% CI = 0.97 to 1.00).

Discussion

The current study aimed to investigate the validity, sensitivity and reliability of a novel on bike device that uses direct drag for the real-time measurement of a cyclist's CdA. Results of the study demonstrate that within both wind tunnel and velodrome testing conditions, Body Rocket measured CdA were strongly correlated with, and sensitive to, the calculated change arising from known quantities of drag resistance being added to the bicycle. Body Rocket was also demonstrated to be a reliable device for the repeated measurement of CdA during indoor velodrome cycling.

The Body Rocket values in the velodrome strongly correlated with those derived from a theoretical first principles approach ($r^2 = 0.99$), as well as from data collected in the wind tunnel ($r^2 = 0.99$), with the regression line closely matching the line of identity (see Figure 2). In the wind tunnel, Body Rocket was able to discriminate between changes in resistive forces generated by all disc sizes with the smallest change being 0.002 m^2 in CdA. A similarly strong correlation was found between theoretical changes in CdA with a rider in situ during wind tunnel testing. However, as shown by Figure 3b, there was a tendency for Body Rocket to record lower CdA values than theoretically derived as disc size increased resulting in a deviation from the line of identity. This could be due to changes in the interaction between disc and rider wake characteristics with increasing disc sizes.

The small limits of agreement and minimal bias, coupled with the strong correlation between wind tunnel and velodrome data, indicate that Body Rocket can identify changes in CdA despite small positional variations of the cyclists in the velodrome environment. Indeed, given the near perfect correlation within the wind tunnel environment between Body Rocket and theoretical CdA values (see Figure 2), the tendency for reduced CdA values in the velodrome is likely due to variation in the cyclist's ability to maintain a consistent speed or position within increasing disc size (see Figure 3). Further, and as demonstrated by the wind tunnel data (see Figure 3b), deviation from the line of identity with increasing disc size could also be attributed to interactions between disc and rider wake characteristics. Similar findings have been reported by Kordi et al. [10].

The Bland-Altman plot shown in Figure 4 demonstrates small, but increased, residual values between wind tunnel derived and velodrome derived changes in CdA, suggestive of increased within participant variability rather than drift within the Body Rocket. Moreover, as suggested by previous research [19], it is also likely the tendency for an underestimation of CdA may have arisen from the velodrome architecture. As the only influencing factors on Body Rocket drag readings are the air speed (and density), and the rider's position (directly affecting CdA), when the rider moves through the velodrome banking (leaning the bike) the measured air speed will be slightly faster than is experienced by their body as the air speed sensor is positioned slightly lower (below the handle bars) than their centre of surface area. Therefore, the direction of the air travelling over the body will have an induced yaw and upward direction over the body presenting a different flow dynamic and surface area (i.e. affecting the CdA), ultimately resulting in a slightly lower value compared to the wind tunnel.

Comparisons of validity data across different aerodynamic devices is challenging due to different methods used to collect data. The current study captured CdA data collected in the wind tunnel and velodrome, using known CdA benchmarks to change drag coefficients and found a sensitivity of 0.002 m^2. Using the same disc-based approach in wind tunnel and velodrome environments, Kordi et al. [10] demonstrated a similarly high sensitivity of the Notio Aerometer device (~0.002 m^2). However, in contrast, Bruez et al. [12] found a 4.8% difference between Notio Aerometer and theoretically calculated CdA values using a similar disc-based (12 & 15 cm discs) benchmarking approach, albeit on an outdoor out-and-back road segment.

Other studies have relied on changes in rider position to determine sensitivity of detection of CdA values, which are in turn compared to mathematical models [11, 14]. Using this positional change approach, Valenzuela et al. [11] demonstrated that the Notio Aerometer device is capable of discerning large variations in CdA (i.e. upright to aero positions with a mean change of ~0.07 m^2) but was not sensitive enough to identify small variations in CdA caused by helmet (~0.008 m^2) or wheel changes (~0.006 m^2). Using a similar approach, Ordiñana-Pérez et al. [14] suggest that the Notio Aerometer used in their study was not able to statistically discern between three different aerodynamic positions maintained by cyclists whilst riding within a velodrome, reporting a mean change of 0.009 m^2. Interestingly, CdA values for Notio Aerometer were compared to two mathematical approaches, which were also not able to statistically identify the changes in rider position. The Notio Aerometer was found to produce CdA values between 2 and 4% lower than the mathematical models, which is much larger than shown by Kordi et al. [10]. It is therefore unclear how the methods used to investigate the sensitivity of CdA measurement devices impact on results obtained.

Results of the current study demonstrate a high level of reliability within the Body Rocket system from the repeated velodrome runs. The mean coefficient of variation from the 8-lap effort was 1.67% (90% CI = 1.20 to 2.86%) with an ICC of 0.99 (90% CI = 0.97 to 1.00), and an absolute typical error of 0.004 m^2

(90% CI = 0.003 to 0.005 m^2). Like validity comparisons, the comparison of reliability data across different aerodynamic devices is challenging due to different methods used to collect data, and differences in cycling abilities and experience of study participants. Despite all being experienced track riders, participants in the current study were all amateur cyclists competing at regional or national level. Using a similar study population, Valenzuela et al. [11] reported an ICC of 0.92 (90%CI = 0.89 to 0.95) and a typical error of 0.015 m^2 (90% CI = 0.014 to 0.017) from repeated velodrome runs using the Notio Aerometer. Also using the Notio Aerometer, Kordi et al. [10] demonstrated a lower CV (0.47%; range = 0.16 to 0.69%), ICC (0.99; range = 0.98 to1.00) and absolute typical error (0.0017 m^2; range = 0.0013 to 0.0023 m^2) than the current study. However, participants within Kordi's study were elite track riders (including several track cycling World Champions and medallists) and so differences in repeatability measurements are likely due to their ability to more consistently maintain a superior aerodynamic position over the duration of the effort. Moreover, the higher bike speed used during testing (50 km/h) in Kordi's study is likely to result in Reynolds number values indicative of more stable and lower CdA values due to air speed being consistent turbulent airflow [20]. The slower bike speed used by participants in the current study (40 km/h) is below the critical Reynolds value where airflow around the cyclist will be an unstable mixture of laminar and turbulent flow, likely causing more unstable and higher CdA values during testing [20]. Interestingly, when a standardised typical error approach [21] is used (dividing change in mean, typical error and confidence limits by the *pure* between-subject standard deviation for all trials), values were slightly lower in the current study than that of Kordi et al. [10] (current study = 0.11, 90% CI = 0.08 to 0.13 vs. Kordi et al. = 0.13, 90% CI = 0.11 to 0.18).

Bruez et al. [12] found similar levels of reliability using the Notio Aerometer to quantify the CdA of riders in outdoor conditions (ICC = 0.98) using a flat out-and-back course. Therefore, despite the aforementioned lower sensitivity for Notio in the outdoor setting, their study demonstrated good levels of reliability, albeit with all data obtained from one participant. Similarly, although data from the current study suggest that Body Rocket provides good validity, sensitivity and reliability in wind tunnel and indoor velodrome environments, the application of the technology is to provide real-time CdA estimation outside on the road. Future research is therefore required to validate Body Rocket within a more ecologically valid setting (e.g. with variable wind speeds and directions as well as elevation changes). In addition, the Body Rocket limits of detection for changes in CdA were not established in the current study, with 0.002 m^2 representing the smallest change in CdA between 50 and 60mm disc sizes. Therefore, further research is required to establish the smallest change in CdA that can be reliably detected using the system.

Conclusion

The results of this study demonstrate that Body Rocket is a valid and reliable device for the real-time measurement of direct drag force derived CdA during velodrome cycling. The high level of sensitivity to changes in CdA (0.002 m^2) suggest it has the potential to provide valuable information to coaches and riders performing aerodynamic testing of changes in position or when trialling new equipment. However, further research is required to confirm its validity and reliability in outdoor conditions.

Contributions

Contributions to conception and design: JH, SG, CRJF, CB

Acquisition of data: JH, CRJF, CB

Analysis and interpretation of data: JH

Drafted and/or revised the manuscript: All authors

Final approval of the version to be published: All authors

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