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Original Article

Validity of bicycle mounted pitot tubes for real-time analysis of cyclist's drag area for outdoor testing

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Abstract: Wind tunnel experiments were conducted to assess the validity of the outdoor use of two commercially available bicycle-mounted static pitot tubes (BMPT), viz the Notio Konect™ [NK] and Aeropod™ [AP]. Three different experiments were conducted by comparing wind tunnel speed to the measured wind speed by both BMPTs. The sensors are tested, firstly, in a wide range of wind speeds (8 to 20 m/s); secondly in a range of yaw angles (0° to 20°) and, thirdly, for three riders' positions. The results show that both sensors require calibration to ensure that the measured wind speed matches that of the wind tunnel. After calibration at 14 m/s, the measured wind speed of the NK is within 0.22% over the velocity range up to 20 m/s. Instead, an error is present in the wind speed measured by the AP, which grows with the velocity offset to that of the calibration and reaches -2.51% at 20 m/s. Further both the NK and AP did not measure the wind speed accurately when yaw angles were introduced, this resulted in an error of 5.8% for the AP and 3.9% with a yaw angle of 20°. Besides, rider position influences the measurement of the wind speed for both the NK and AP. We concluded that both the NK and the AP are not suitable for outdoor testing when crosswinds occur. Furthermore, before every position change, it is necessary to do a calibration run to collect accurate results.

Keywords: cycling, aerodynamics, wind tunnel, coefficient of drag.

1. Introduction

At the elite level, cycling and triathlon time-trials (TT) are performed at speeds over 50 km/h (Lucia, Hoyos, & Chicharro, 2001). At those velocities, up to 90% of the total resistance comes from air resistance (Martin, Gardner, Barras, & Martin, 2006). Being able to minimise the air resistance, also referred to as aerodynamic drag (or more specifically, to increase the mechanical power output to air resistance ratio) is a key determinant of performance in TT events (Peterman, Lim, Ignatz, Edwards, & Byrnes, 2015). Thus, it is of interest to those competing in TTs to be able to quantify, reduce and optimise their air resistance to improve their performance. The air resistance, D [N] of an object immersed in the air is expressed by:

$$D = 1/2\,\rho v^2 C_D A$$

where ϱ is the air density, v [m^2] is the speed of the object relative to the surrounding air, CD is the drag coefficient and A the frontal area of the object. The aerodynamic performance of a cyclist is generally quantified by the drag area, CdA. For accurate and repeatable measurement of the drag area, the use of force balances in wind tunnels is considered to be the 'gold standard'. However, wind tunnels do not always accurately resemble real-world flows (Debraux, Grappe, Manolova, & Bertucci, 2011). In addition, wind tunnel use is expensive and relatively inaccessible (Martin et al., 2006). With the introduction of mobile power meters that measure mechanical power output, multiple mathematical models have been developed for the estimation of the drag area (CdA) of a rider in motion in steady meteorological conditions (quiescent air) (Garcia-Lopez, Ogueta-Alday, Larrazabal, & Rodriguez-Marroyo, 2014; Martin et al., 2006). It is generally assumed that the latter conditions can be approximated in indoor velodromes with a high level of agreement to wind tunnel measurements (Martin et al., 2006). Although this has made aerodynamic testing less expensive and more accessible, they remain limited to the indoor environment.

Recently, these mathematical models have become available in commercial software products that allow the measurement of the rider's CdA in the presence of headwind by measuring the rider's speed relative to the air. This air speed is generally measured using bicycle mounted pitot-static tubes (BMPT) such as Notio Konect™ [NP] and AeroPod™ [AP]. Pitot-static tubes are widely used in aeronautics and fluid dynamic research to accurately measure air speed. When used on a bike, the BMPTs collect the wind speed data in conjunction with data collected from other bicycle mounted sensors (such as wheel speed, mechanical power output and bike orientation), making it is possible to compute the cyclists' CdA. It remains unclear, though, in what conditions (more specifically, whether it can be used outdoors) these new sensors provide valuable data. This work aims to clarify in what conditions the first generation BMPTs (i.e. NK and AP) provide reliable data.

When using pitot-static tubes, here simply called pitot tubes, the speed of the rider relative to the air is obtained measuring the stagnation or total air pressure (PT), probed in at the tube's head, the static air pressure (Ps), usually probed by multiple ports on the circumference of the tube and the air density (Ower & Pankhurst, 1977). The air speed then follows from Bernoulli's equation:

$$P_T = P_s + 1/2\,\rho v^2$$

Where 1⁄2 ϱ v^2 is called the dynamic pressure. To be able to measure the rider's wind speed accurately, the pitot tube needs to be designed carefully and the sensor is ideally installed in undisturbed air, meaning that the BMPT should be installed sufficiently from the rider and bike. In practice, however, BMPTs are installed close to the handlebars and rider. Hence, on manufacturer's instructions a calibration procedure is required to correct for the BMPT's measured air speed. It can be assumed that this is easily achieved indoors (i.e. in an indoor velodrome). Previous studies concluded that the real-time CdA measured by the NK in an indoor velodrome showed high reliability and sensitivity (Kordi, Galis, van Erp, & Terra, 2021; Valenzuela et al., 2020). An outdoor assessment of these BMPTs, however, is missing in the literature. Measuring the wind speed of the BMPT at different speeds and yaw angles in a controlled environment such as a wind tunnel can give a good indication of the accuracy of the measured wind speed and, in turn, reflected in the CdA calculations and therefore if its suitability for outdoor use. This information would be highly relevant and useful for riders, coaches, and practitioners who would want to know the limitations and capabilities of these different BMPTs and in which circumstances are better suited to estimate CdA.

To the best of the author's knowledge, no studies have tried to assess the accuracy of the BMPTs measured wind speed. Therefore, this study aims to do so in a range of speeds, yaw angles, and rider positions by wind tunnel experiments.

The goal is firstly, to assess and compare the accuracy of the wind speed measurements of the NK and AP with that of the wind tunnel. Secondly, this work aims to assess the accuracy of wind speed measurements of the NK and AP with various yaw angles. The third goal is to assess and compare if and how different rider positions affect the measurements of the NK and AP.

2. Methods

The design

Two BMPTs were used in this experiment (i.e. Notio Konect™, Montréal, Canada [NK] and AeroPod™, Jupiter, Florida, USA [AP]). Three experiments were done to investigate the accuracy of the BMPT. All measurements were conducted in the Open Jet Facility of the Aerodynamics Laboratories at the Delft University of Technology. This open jet wind tunnel has an octagonal cross-section of 2.85 m × 2.85 m with a contraction ratio of 3:1, which allows the generation of a homogeneous jet at speeds between 4 and 35 m·s-1 with a turbulence intensity below 0.5% (Lignarolo et al., 2014). Measurement in the wind tunnel allowed the comparison of the BMPTs wind speeds to those of the calibrated wind tunnel apparatus.

Firstly, to assess the accuracy of the BMPTs and to what range of wind speeds, both the NK and AP were (separately) placed in free air directly facing the wind tunnel and evaluated at 7 different wind speeds (8, 10, 12, 14, 16, 18, and 20 m/s). The measurements in free air (in absence of bike or rider) are conducted with the sensors aligned with the freestream velocity direction and installed in the center of the wind tunnel jet.

Secondly, to investigate whether the NK and AP are valid for the outside use (i.e. with crosswinds), measurements are conducted at different yaw angles (i.e. 5°, 10°, 15°, and 20°) at 14 m/s and are compared to the expected wind speed with the specific yaw angle at 14 m/s. The expected wind speed is calculated based on the offset from experiment 1 and with U * cos θ.

Thirdly, NK and AP were placed on a TT bike and are evaluated with a rider in 3 different positions (position A = upright; position B = aero; position C = optimised aero; see Figure 1) at 14 m/s. The cyclist was wearing cycling clothing along with a helmet (Bell Star Pro, Bell, United states, CA). The rider is installed on a Cervelo P5 Time Trial (Cervelo INC, Toronto, Canada) bike frame equipped with Shimano Dura Ace C25 wheels (Shimano INC, Osaka, Japan), both fitted with 25 mm tubular tires.

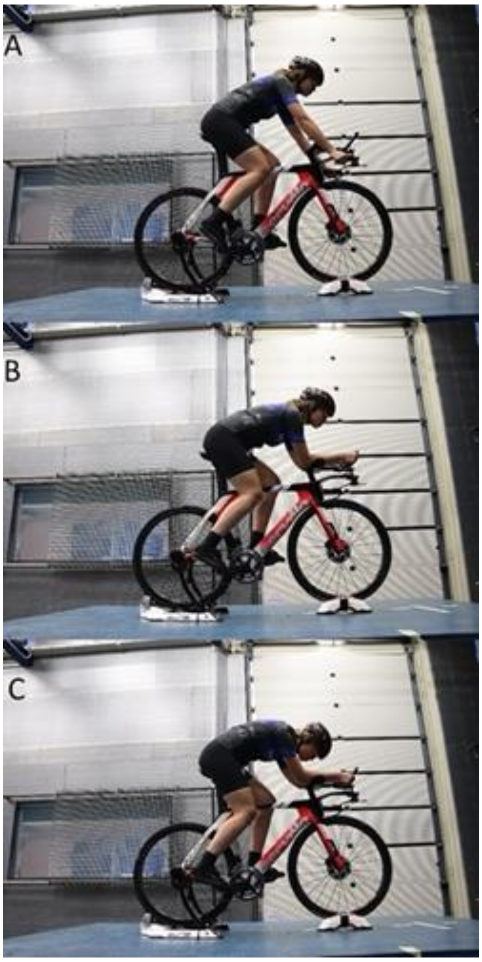

Figure 1: representative example of the three rider positions (upright {[A], aero [B] and optimized aero [C].

In addition, the BMPT wind speeds were corrected, like the manufacturer's prescribed calibration procedure. Each speed was corrected by the relative offset between the measured BMPT and wind tunnel velocity at 14 m/s.

Data analysis

The raw dynamic pressure of the BMPTs (i.e. Notio Konect™ and AeroPod™) was collected and presented in time-average wind speeds (±SD). The observation time of all measured velocities was 30 seconds. The relationship and level of agreement between the wind tunnel wind speed and the wind speed measured by three sensors were analysed by Pearson's correlation coefficients (r), standardized error of estimate (SEE) with 95% confidence intervals, and bias with the limits of agreement (LoA [bias ± 1.96*SD]), using the spreadsheet developed by Hopkins (Hopkins, 2015). The data is presented as pre-and post-calibration at 14 m/s. The differences presented between the wind tunnel and the speed measured by sensors for the different yaw angles and the three different rider positions are presented relative to the reference value obtained by experiment 1 at 14 m/s. The following criteria were adopted to interpret the magnitude of the correlation(r) between the measures: < 0.1 trivial, 0.1-0.3 small, 0.3-0.5 moderate, 0.5-0.7 large, 0.7-0.9 very large, and 0.9-1.0 almost perfect.

3. Results

Without calibration the air speed measured by the NK showed an almost perfect (r = 0.999) relationship, a SEE of 0.009 (CI = 0.006 to 0.022) m/s, a bias of -0.496 (CI = -0.487 to -0.505) m/s and LoA of 0.32 m/s with the wind tunnel speeds (Figure 2 A, B and C). The corrected air speed measured by the AP showed an almost perfect (r = 0.999) relationship, a SEE of 0.090 (CI = 0.056 to 0.222) m/s, a bias of 1.06 (CI = 0.92 to 1.21) and LoA of

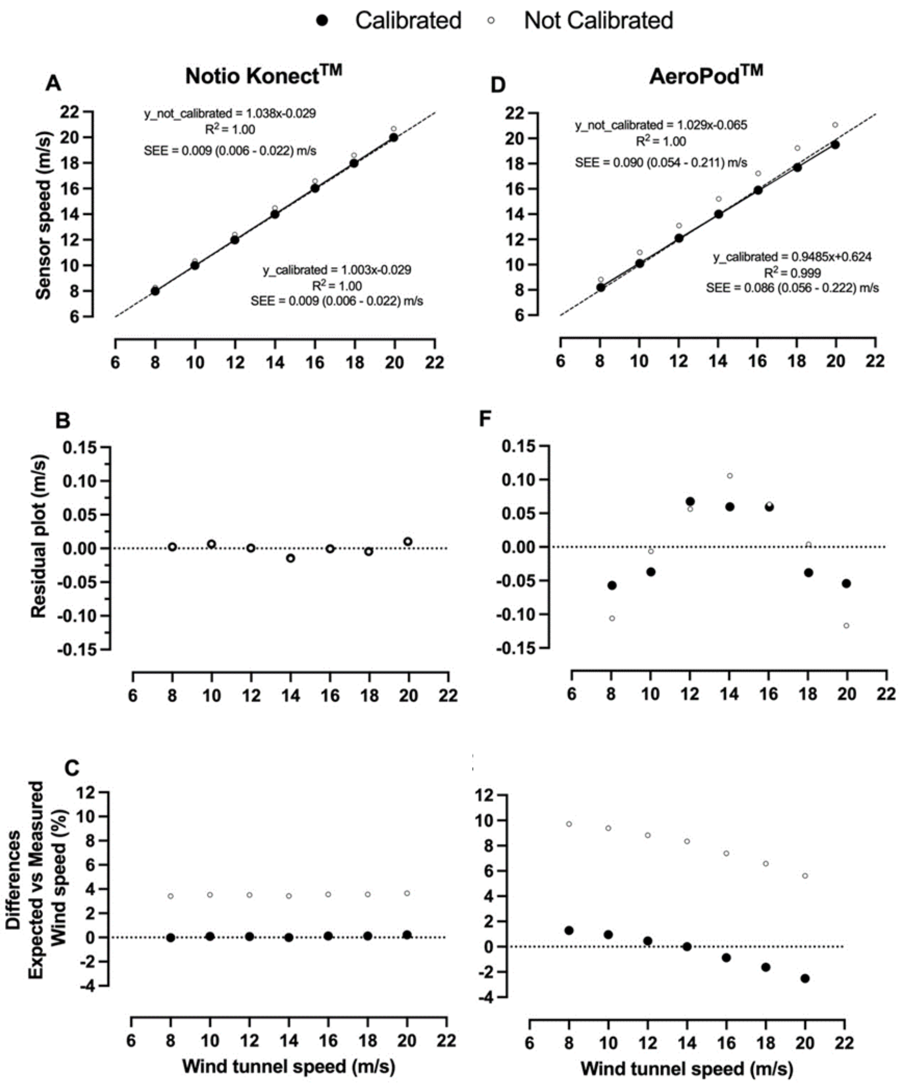

Figure 2: Pearson relationship (A, D), agreement (Bland Altman plot [B, E]) and differences (%) between the measured speed of the Notio Konect™ vs Wind Tunnel speed and the measured speed of the AeroPod™ vs Wind Tunnel speed (C, E). In panels (A, D) the dashed lines represent the perfect regression line, in panels (B, C, E, F) the dashed line represents 0% differences. Abbreviations: SEE, absolute standardized error of estimate.

0.299 m/s with the wind tunnel speed (Figure 2 D, E and F).

When the NK and AP were calibrated, the corrected air speed measured by the NK showed an almost perfect (r = 0.999) relationship, a SEE of 0.009 (CI = 0.006 to 0.022) m/s, a bias of -0.014 (CI = -0.029 to 0.000) m/s and LoA of 0.031 m/s with the wind tunnel speeds (Figure 2 A, B and C). The corrected air speed measured by the AP showed an almost perfect (r = 0.999) relationship, a SEE of 0.086 (CI = 0.054 to 0.211) m/s, a bias of 0.097 (CI = -0.114 to 0.308) and LoA of 0.447 m/s with the wind tunnel speed (Figure 2 D, E and F).

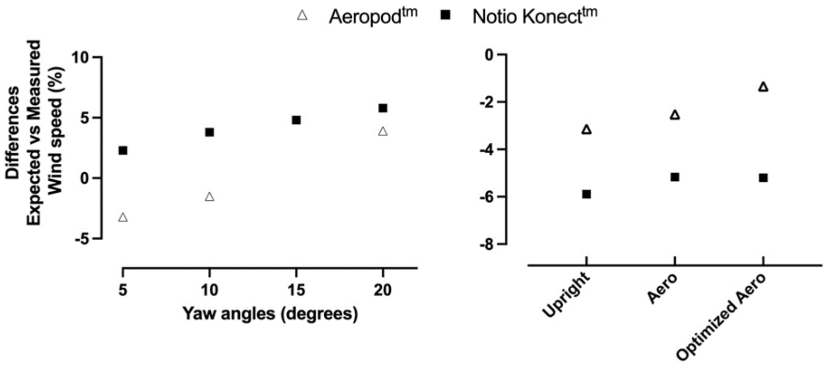

Figure 3: Percentage of differences between the expected (wind-tunnel) and measured wind speed (Notio Konect and Aeropod devices). (A) Differences at 5, 10, 15 and 20º of yaw angles. (B) Differences at Upright, Aero and Optimized positions of the cyclist on the bike.

Figure 3A shows the percentage of differences between the NK and AP measured wind speeds and the expected wind speeds (i.e.; wind-tunnel speeds). The expected wind speeds (i.e.; the product between the wind-tunnel speed and the cousin of the yaw angle) at 5, 10, 15 and 20º were 13.95, 13.79, 13.52 and 13.16 m/s, respectively. The air speeds measured by the NK were 14.27, 14.31, 14.17, and 13.92 m/s, respectively. The wind speeds measured by the AP were 13.51, 13.58, --, and 13.67 m/s, respectively (Due to technical problems, it was not possible to report the wind speed at a yaw angle of 15° degrees of the AP). Overall, NK overestimated the wind speed (from 2.3 to 5.8%), while the measurements of AP showed more variability (from -3.2 to 3.9%) (Figure 3A).

Figure 3B shows the percentage of differences between the NK and AP measured wind speeds and the wind-tunnel speed (i.e.; 14 m/s) in the three analyzed positions of the cyclists on the bike (A-upright, B-aero, C-optimized) at a yaw angle of 0º. NK (13.17, 13.28 and 13.27 m/s, respectively) and AP (13.60, 13.69 and 13.86 m/s, respectively) measured wind speeds were affected by the position of the cyclist on the bike.

4. Discussion

The four principle findings of this study were: 1) Once the NK has had its 'offset' adjusted by the calibration, it can be used over a wider range of wind speeds whilst the AP uses the calibration for specific, targeted speed ranges and therefore can only be used at the calibrated speed (and a narrow range around it); 2) Both the NK and AP did not measure the wind speed accurately when a range of yaw angles was introduced meaning that they are better suited for indoor cycling where cross-winds are non-existent and; 3) the measurement of wind speed was at least 5.2% (NK) and 1.4% (AP) lower than the actual wind speed when mounted on a bicycle with a rider in different positions. These results indicate that both BMPTs are not suitable for outdoors testing with crosswinds. Furthermore, calibration procedures should be in place with substantial changes in bike position. 4) That the results of the NK and the AP cannot be interchanged. After calibration the NK has a large range at which it can be use outside the calibration value which contrasts with the AP. In addition, there is no systematic change for both the NK and AP with different yaw angles.

The validity of both BMPTs was assessed by exposing NK and AP to a range of wind speeds and positions. It is shown that before calibration, the NK had a consistent over-prediction of each wind speed by ~3.5%. After calibration at 14 m/s, the NK measured the wind speed with a very high level of accuracy at all speed ranges (from 8 to 20 m/s). This is in agreement with previous literature which found that the NK can reliably calculate CdA (Kordi, Galis, van Erp, & Terra, 2021; Valenzuela et al., 2020). However, comparing the results in detail is somewhat difficult due to the different nature of the the studies (wind speed vs CdA). In comparison, AP did display a very strong relationship with increases in wind speed by the wind tunnel, but the slope was 0.9485 (Figure 2 D) indicates that there is a small error in measurements. Such error in the measured velocity propagates into the estimated aerodynamic performance of a rider. This would for a hypothetical cyclist with a CdA of 0.217 mean that, when the AP is calibrated at 14 m/s and, instead, it is used at 12 m/s, the data presented in this experiment suggests that the AP may underestimate the CdA with 1.4% or a CdA of 0.214. Such error could also explain why in a dynamic setting the AP (i.e. PowerpodTM) was not able to calculate power output accurately (Merkes, Menaspà, & Abbiss, 2019). Both manufacturers state that their respective BMPT should be calibrated at the approximate wind speeds they intend to be used and as such both display at a high level of accuracy when this is done. The calibration procedure the end user goes through adds an additional layer, with the diligence used in performing a good calibration ride which in turn affects the ability of the device to reliably measure wind speed. However, in this work, it is observed that the NK, in comparison to the AP, can be used over a wider range of speeds after only a single calibration ride.

In experiment 2, the NK and AP were used to measure the wind speed at different yaw angles to simulate crosswinds, which cyclists may experience when riding outdoors. The data shows that both sensors were unable to accurately measure the wind speed within a range of yaw angles. The differences between the actual wind speed and the measured air speed ranged from 2.3 to 5.8% for the NK and -3.2 to 3.9% for the AP. To put this into context, if a cyclist with a CdA of 0.217 is riding with 14 m/s and is exposed to a pure side wind of 1.22 m/s (resulting in a yaw angle of 5 degrees), the NK will overestimate the wind speed by 2.3% (i.e. CdA of 0.207) and the AP underestimate the wind speed with 3.2% (i.e. CdA of 0.233). This clearly shows that the results of both the devices (NK and AP) are not interchangeable. Hence, the estimated aerodynamic performance of these BMPTs should be considered with care when used outdoors. Such error in the measured wind speed and estimated CdA in the presence of crosswinds can be remedied by using more advanced pitot tubes that also allow measurement of the direction (angle) of the incoming air in addition to the velocity magnitude.

Once the BMPTs were mounted on the bike with a rider in the three 'standard' race positions (upright, aero, and optimized aero position), differences were measured of -5.2% (upright vs aero) and -5.8% (upright vs optimized aero) for the NK and -1.3% (upright vs aero) and -3.1% (upright vs optimized aero) for the AP between the actual and measured wind speeds. This variation in wind speed is larger than the expected differences between the aero and optimized aero positions found by Garcia-Lopez et al. (2014) (Garcia-Lopez, Ogueta-Alday, Larrazabal, & Rodriguez-Marroyo, 2014). This shows that changing the rider's position introduces errors in the resulting CdA and, so, that recalibration between these positional changes is necessary for accurate results. It should also be mentioned that any calibration ride is prone to error (for example as the consequence of crosswinds) and so it could be more accurate to place the BMPT sufficiently far from the bike and rider (upstream or at sufficient lateral distance) so that the BMPT measured pressure is not affected by the cyclist.

The results of this study highlight that the usefulness and reliability of these device is ultimately down to the diligence of the end user. Both devices (i.e. NK and AP) should be calibrated according the manufactures recommendation. Furthermore, the location of the devices on the bike, riders' positions, location (indoors vs outdoors) and testing protocol should be considered before using by the end user.

5. Limitations and Future Studies

The main limitation of this study was that the study was conducted in a wind tunnel setting rather than in a real outdoor setting, which is not an ecological measure of the aerodynamic drag in cycling. However, this is the only option to standardize and compare wind speeds. Other important measures that the BMPTs uses to make the calculation of CdA (such as are the rolling, slope resistance, temperature, barometric pressure, and the mathematical model) used to determine the total resistance were not investigated and their variation on the final values are CdA are not known. Therefore, it is unclear how the BMPTs would perform in a real outdoor setting where elevation and road surface changes also influence the measurements of the CdA.

6. Conclusions & Practical Applications

In conclusion, these results show that both sensors require calibration (as per manufactures guidelines) to ensure that the measured wind speed matches that of the wind tunnel. These data suggest that the NK can measure a range of wind speeds to a high agree of accuracy with whereas the AP needs to be recalibrated when measurements are done at different speeds from the calibration. Furthermore, both the NK and AP did not measure the wind speed accurately when either yaw angles were introduced or when there was a change in rider position. Hence, for accurate estimation of a rider's CdA it is recommended, firstly, to use the NK instead of the AP, especially when riding at a speed that deviates from the calibration speed; secondly, to only use these BMPTs in outdoor situations when crosswinds are absent; and, thirdly, to perform a calibration run after every significant change in position. The calibration procedure the end user goes through adds an additional layer, with the diligence used in performing a good calibration ride which in turn affects the ability of the device to reliably measure wind speed. Manufacturers should aim to improve their BMPT for outside testing (i.e. yaw angles). This will make a product highly valuable for professional cyclists and triathletes when it would be possible to collect real-time CdA values in a race setting.

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Disclosure of interest

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