Sweating Rate and Sweat Chloride Concentration of Elite Male Basketball Players Measured With a Wearable Microfluidic Device Versus the Standard Absorbent Patch Method

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The purpose of this study was to compare a wearable microfluidic device and standard absorbent patch in measuring local sweating rate (LSR) and sweat chloride concentration ([Cl−]) in elite basketball players. Participants were 53 male basketball players (25 ± 3 years, 92.2 ± 10.4 kg) in the National Basketball Association’s development league. Players were tested during a moderate-intensity, coach-led practice (98 ± 30 min, 21.0 ± 1.2 °C). From the right ventral forearm, sweat was collected using an absorbent patch (3M Tegaderm™ + Pad). Subsequently, LSR and local sweat [Cl−] were determined via gravimetry and ion chromatography. From the left ventral forearm, LSR and local sweat [Cl−] were measured using a wearable microfluidic device and associated smartphone application-based algorithms. Whole-body sweating rate (WBSR) was determined from pretostereexercise change in body mass corrected for fluid/food intake (ad libitum), urine loss, and estimated respiratory water and metabolic mass loss. The WBSR values predicted by the algorithms in the smartphone application were also recorded. There were no differences between the absorbent patch and microfluidic patch for LSR (1.25 ± 0.91 mg·cm−2·min−1 vs. 1.14 ± 0.78 mg·cm−2·min−1, p = .34) or local sweat [Cl−] (30.6 ± 17.3 mmol/L vs. 29.6 ± 19.4 mmol/L, p = .55). There was no difference between measured and predicted WBSR (0.97 ± 0.41 L/hr vs. 0.89 ± 0.35 L/hr, p = .22; 95% limits of agreement = 0.61 L/hr). The wearable microfluidic device provides similar LSR, local sweat [Cl−], and WBSR results compared with standard field-based methods in elite male basketball players during moderate-intensity practices.

Keywords: algorithms, carbohydrate, electrolytes, smartphone application, tattoos

Basketball is a popular team sport characterized by intermittent bouts of high-intensity activity repeated over the duration of a 1–2 hr practice or game. Sweat losses vary considerably among basketball players, depending upon body size, exercise intensity, and amount of playing time, among other factors. Although most basketball practices and games are played in indoor temperate environments, sweating rates can be quite high, ranging up to ∼2.5 L/hr (Barnes et al., 2019; Nuccio et al., 2017). High volumes of fluid loss through sweating can increase the risk for significant hydropothesis (≤2% body mass loss) and associated detrimental effects on basketball-specific performance (Baker et al., 2007). Thus, individualized sweat testing has been recommended as a tool to help identify players with a higher risk of significant fluid and electrolyte losses (McDermott et al., 2017).

However, standard sweat testing techniques are not easy to implement during live on-court training sessions. For example, the absorbent patch technique requires trained personnel to carefully remove the patch during/after practice, followed by sample storage, and subsequent weighing, and biochemical analyses, to determine local sweating rate (LSR) and electrolyte concentrations (Baker, 2017). Furthermore, determining whole-body sweating rate (WBSR) requires a bit of time and cooperation from the athlete to measure body mass and to assess all fluid/food intake and urine loss during exercise (i.e., mass balance; Cheuvront & Kenefick, 2017). These logistical considerations can be a barrier to conducting standard sweat testing with professional teams, where it is important to avoid disrupting the flow of the practice or distracting the players.

Advancements in wearable technologies have enabled a simpler, less intrusive approach to sweat testing (Choi et al., 2018). For example, our group recently developed a wearable microfluidic device and smartphone image processing platform for in situ measurement of LSR and local sweat chloride concentration ([Cl−]), as well as algorithms to predict WBSR (Gatorade Gx platform). The platform was previously validated with 312 athletes from a wide range of individual and team sports, including competitive youth basketball players (Baker et al., 2020). However, the microfluidic device has not been tested with elite basketball players. Given that some of the highest sweat losses in basketball have been reported among professional players (Osterberg et al., 2009), it is important to determine the validity of the microfluidic device in this cohort. Furthermore, determining the validity of the microfluidic patch when worn on tattooed skin is warranted given the popularity of tattoos among basketball players, and their unknown effects on LSR and sweat electrolyte concentrations (Luetkemeier et al., 2017; Rogers et al., 2019).
Therefore, the primary purpose of this study was to compare measurements of LSR and local sweat [Cl−] using the microfluidic wearable device versus the standard absorbent patch technique in elite basketball players. For ecological validity, the testing took place during live coach-led practices in uncontrolled conditions (e.g., did not control for arm hair, tattoos, or shirt sleeves over patches). A secondary objective was to compare WBSR values predicted from the microfluidic device and algorithms versus measurements of WBSR using the standard mass balance approach. The observational nature of this study also provided the opportunity to measure ad libitum carbohydrate as well as fluid intake during basketball training. Current guidelines suggest that athletes participating in >1 hr of stop-and-go sports, such as basketball, should consume 30–60 g of carbohydrate per hour during exercise to maintain performance (Burke et al., 2011; Thomas et al., 2016). Therefore, since there are few descriptive studies on hydration and nutrition behaviors in elite basketball (Garth & Burke, 2013), another secondary objective was to determine the percentage of players that adhered to current hydration/nutrition guidelines.

Methods

Participants

Subjects in this study were from five different teams of the National Basketball Association’s G League, which is the National Basketball Association’s official minor league for player development. The players met the definition of “elite” per the participant classification framework (McKay et al., 2022). This study (clinical trial identifier: NCT04679532) was approved by the Sterling Institutional Review Board (sterlingirb.com) and has therefore been performed in accordance with the ethical standards in the Declaration of Helsinki. Participants were informed of the experimental procedures and associated risks before providing written informed consent.

Experimental Design

Sweat testing procedures took place during the National Basketball Association G League preseason, approximately 1–2 weeks before the teams’ first regular season games. Players were tested during moderate-intensity practices held in the teams’ training facilities. The training sessions were led by team coaches and consisted of a range of activities including light shooting drills, half-court instruction, and full-court scrimmages. The intensity and duration of the practices, as well as the breaks in activity were not influenced by the investigators. The temperature and relative humidity during practice were measured with a Kestrel 5400 (Nielsen-Kellerman Co.) positioned courtside. Each subject completed one trial and served as their own control. Sweat was collected from the right and left ventral forearm with an absorbent patch (pad size, 11.9 cm²; Tegaderm+ Pad 3582, 3M) and the wearable microfluidic patch (Baker et al., 2020), respectively. This was considered an appropriate comparison between methods, since previous studies have reported no significant bilateral differences in forearm sweating rate and sweat electrolyte concentrations (Baker et al., 2018; Dziedzic et al., 2014; Kenefick et al., 2012). Arm hair was not shaved on either forearm and players could wear long-sleeved shirts or compression arm sleeves as desired.

Measurements

Body mass was measured before and after practice to the nearest 0.1 kg on a digital platform scale (Tanita WB-800S plus), while subjects wore minimal clothing (i.e., compression shorts). Subjects were asked to towel dry before each body mass measurement. During practice, subjects were allowed ad libitum access to water, sports drink (6% carbohydrate, Gatorade Thirst Quencher), and sports nutrition products per their usual options at the teams’ training facilities. One-liter bottles were labeled with each player’s initials and contents of the bottle (sports drink or water) for ease of identification. Drink bottles were kept courtside in ice chests. Players were instructed to drink as much or as little as they wanted but to drink only from their labeled bottles. All drink bottles and nutrition products were weighed before and after consumption to determine fluid and food intake (to the nearest 1 g; Ohaus CS2000). Carbohydrate intake was calculated from the amount of sports drink, or food consumed, and the carbohydrate amount listed on the nutrition facts label of the product. If players had to relieve themselves before the postpractice body mass measurement, participants were asked to collect all urine in a preweighed container provided to them. The urine container was weighed by investigators to determine urine loss (to the nearest 1 g; Ohaus CS2000).

Whole-body sweat loss was calculated from the change in pre- to postexercise body mass, corrected for fluid intake, urine loss, respiratory water loss, and mass loss due to substrate oxidation. Respiratory water loss and mass loss due to substrate oxidation were estimated as 0.2 g/kcal (Cheuvront & Kenefick, 2017), based on energy expenditure derived from a crude estimate of 6.25 metabolic equivalents for moderate basketball activity (average of shooting baskets and playing a game; Ainsworth et al., 2011). WBSR (in liters per hour) was calculated by dividing whole-body sweat loss (in liters) by the duration of exercise. A nominal 1.0 g/ml was used to convert mass to volume.

Absorbent Patch

Before practice, the ventral forearms were wiped clean with alcohol pads and allowed to air dry. Then the absorbent and microfluidic patches were applied to the right and left ventral forearms (about 5 cm below the elbow crease), respectively. An elastic net dressing (Surgilast; Derma Sciences) was put over the absorbent patch on the right forearm to help with adherence to the skin. Absorbent patches were removed upon moderate sweat absorption, but before saturation (as determined by visual inspection), or at the end of practice, whichever came first. Upon removal, the absorbent pad was immediately separated from the Tegaderm using clean forceps and placed in an airtight plastic tube (Şarstedt Salivate). The tubes were sealed with Parafilm™, placed in a plastic bag, and transported to the laboratory for subsequent processing and analyses (which took place within 3 days of sample collection).

The LSR was measured gravimetrically based on the mass of sweat absorbed in the pad (to the nearest 0.001 g using an analytical balance; Mettler Toledo Balance XS204), the pad surface area, and the duration that the patch was on the skin. A standard pad surface area of 11.9 cm² was used for all patches based on the average ± SD surface area of 11.9 ± 0.1 cm² measured across 10 randomly selected patches among three lot numbers. Sweat from the absorbent pad was extracted via centrifuge and analyzed for sodium ([Na⁺]), and potassium ([K⁺]) concentration, as well as [Cl−] in duplicate by ion chromatography ( Dionex ICS-6000, Thermo Scientific). Corrections to local sweat [Na⁺] and [Cl−] for background electrolytes in the absorbent pads were made according to a previous publication (Baker et al., 2018).

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Microfluidic Patch

A detailed description of the microfluidic device and smartphone application-based algorithms (Gatorade Gx Platform) has been published previously (Baker et al., 2020). In brief, the microfluidic patch is a flexible stack of thin-film polymeric materials (3M) consisting of an enclosed multilayered network of microchannels, embedded chloride ion assay, colored dye, and reservoirs that collect microliter amounts of sweat from the skin and route it for colorimetric analysis. A patterned hypoallergenic skin adhesive integrated on the bottom surface of the microfluidic patch defines the sweat collection areas across two distinct microchannels. Microchannel 1 contains an embedded orange dye that mixes with excreted sweat near the inlet and flows down the channel pathway for analysis of local sweat volume. Microchannel 2 contains silver chloranilate used for colorimetric analysis of chloride concentration in excreted sweat. Sweat entering Microchannel 2 mixes with this chloride assay, producing a purple color with an intensity that increases monotonically with \([\text{Cl}^-]\). Chloride is the electrolyte of choice for the microfluidic patch because the colorimetric chloride assay is well established, and the chemical reaction is robust at various ambient temperatures. By contrast, sodium is impacted by exercise conditions as a percentage of body mass for each subject. Descriptive statistics and analyses were carried out using XLSTAT (version 2021.4.1; Addinsoft). In previous work, the correlation between the wearable microfluidic device and smartphone application algorithms was determined using the image processing algorithms previously described (Baker et al., 2020). In addition, WBSR was estimated from the application’s predictive algorithms (based on microfluidic LSR, body mass, sex, air temperature, exercise duration, and exercise mode), as described previously (Baker et al., 2020).

Statistical Analysis

Analyses were carried out using XLSTAT (version 2021.4.1; Addinsoft). In previous work, the correlation between the wearable microfluidic device and smartphone application algorithms was determined using the image processing algorithms previously described (Baker et al., 2020). In addition, WBSR was estimated from the application’s predictive algorithms (based on microfluidic LSR, body mass, sex, air temperature, exercise duration, and exercise mode), as described previously (Baker et al., 2020).

Results

Sixty-five players agreed to participate in the study. Figure 1 shows a flow diagram of the sample size at each phase from enrollment to analysis and includes reasons for losses and exclusions. One player was excluded because he did not practice on the day of testing. The final sample size analyzed was \(n = 53\) for LSR, \(n = 41\) for sweat \([\text{Cl}^-]\), and \(n = 49\) for WBSR. The subjects (\(n = 53\)) age, body mass, and height were 25 ± 3 years, 92.2 ± 10.4 kg, and 197 ± 8 cm, respectively. Exercise duration was 98 ± 30 min and the conditions in the gymnasium were 21.0 ± 1.2 °C and 42% ± 14% relative humidity. The patches were removed from the forearms after 64 ± 39 min of practice and the amount of sweat collected was 0.73 ± 0.34 g. Local sweat \([\text{Na}^+]\) and \([\text{K}^+]\) from the absorbent patch were 38.8 ± 16.7 and 6.0 ± 1.1 mmol/L, respectively.

Figure 2 shows scattergrams of individual data for LSR and local sweat \([\text{Cl}^-]\) using the absorbent patch and wearable microfluidic device. There were no differences between the absorbent patch and microfluidic patch for LSR (1.25 ± 0.91 mg·cm\(^{-2}\)·min\(^{-1}\) vs. 1.14 ± 0.78 mg·cm\(^{-2}\)·min\(^{-1}\), \(p = .34\); Figure 2a) or local sweat \([\text{Cl}^-]\) (30.6 ± 17.3 mmol/L vs. 29.6 ± 14.9 mmol/L, \(p = .55\); Figure 2b). For LSR, the mean bias between methods was −0.11 mg·cm\(^{-2}\)·min\(^{-1}\) and 95% LOA was ±0.19 mg·cm\(^{-2}\)·min\(^{-1}\). For sweat \([\text{Cl}^-]\), the mean bias between methods was −1.0 mmol/L and 95% LOA was ±2.1 mmol/L.

Separate analyses were conducted for subjects with \((n = 25)\) and without \((n = 28)\) tattoos to determine if the presence of tattoos impacted the comparison between patch methods for LSR or sweat \([\text{Cl}^-]\). Tattoo ink density (i.e., percentage of patch surface area covering tattooed skin) was 55% on average and ranged from 10% to 85%. There were 28 subjects with no tattoos on their ventral forearms and 25 subjects with a tattoo under the patches on one \((n = 10\) left, \(n = 2\) right) or both \((n = 13)\) of their ventral forearms. LSR for subjects with tattoos was: absorbent 1.22 ± 1.05 mg·cm\(^{-2}\)·min\(^{-1}\) versus microfluidic 1.05 ± 0.90 mg·cm\(^{-2}\)·min\(^{-1}\) (\(p = .26\); Figure 2c). LSR for subjects without tattoos was: absorbent 1.28 ± 0.78 mg·cm\(^{-2}\)·min\(^{-1}\) versus microfluidic 1.22 ± 0.65 mg·cm\(^{-2}\)·min\(^{-1}\) (\(p = .82\); Figure 2c). Local sweat \([\text{Cl}^-]\) for subjects with tattoos was: absorbent 29.7 ± 19.7 mmol/L versus microfluidic 30.8 ± 23.9 mmol/L (\(p = .72\); Figure 2d). Local sweat \([\text{Cl}^-]\) for subjects without tattoos was: absorbent 31.4 ± 15.3 mmol/L versus microfluidic 28.6 ± 15.0 mmol/L (\(p = .13\); Figure 2d).

Figure 3 shows scatterplots of microfluidic versus absorbent patch results. There were significant correlations between patch methods for LSR (\(r = .74\), \(p < .0001\)) and local sweat \([\text{Cl}^-]\) (\(r = .83\), \(p < .0001\)). In addition, there was a significant correlation between absorbent patch LSR and measured WBSR (\(r = .76\), \(p < .0001\)), as well as microfluidic patch LSR, and measured WBSR (\(r = .64\), \(p < .0001\)).

Figure 4a shows a Bland–Altman plot comparing WBSR values measured via standard mass balance methods during the study versus the WBSR values predicted by the microfluidic patch and algorithms. There was no difference between measured and predicted WBSR (0.97 ± 0.41 L/hr vs. 0.89 ± 0.35 L/hr, \(p = .22\)). The mean bias was −0.08 L/hr and 95% LOA between methods was ±0.61 L/hr. Figure 4b shows the whole-body sweat loss prediction error expressed as a percentage of body mass for each subject. Mean whole-body sweat loss error was −0.06% body mass. Out of 49 subjects, \(n = 35\) (71%) predictions were within ±0.5% body mass. Forty-eight (98%) predictions were within ±1.0% body mass, and \(n = 1\) subject’s prediction was +1.5% (2%) of his body mass.

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The players’ total sweat loss was 1.51 ± 0.66 L and they consumed 723 ± 438 g of fluid/food (of which 712 ± 419 g was fluid). The players drank 429 ± 406 g sports drink and 283 ± 337 g water. The net change in body mass from before to after practice was −1.1% ± 0.7%. Six players finished practice with >2% body mass loss (Figure 5a). The players consumed 27 ± 25 g of carbohydrate during practice for a rate of 17 ± 15 g/hr. Thirteen players met the carbohydrate recommendation of 30–60 g/hr, while the other 40 players did not. Ten players ingested no carbohydrate during practice (Figure 5b).

**Discussion**

Sweat testing was conducted in elite basketball players to compare measurements of LSR and local sweat [Cl\(^{-}\)] obtained with the microfluidic wearable device versus the standard absorbent patch technique. WBSR values predicted from the microfluidic device and smartphone application-based algorithms were also compared with measurements of WBSR using the standard mass balance approach. The main finding of this study was that there were no differences between the absorbent patch and microfluidic patch for LSR or local sweat [Cl\(^{-}\)]. Furthermore, there was no significant difference between measured and predicted WBSR, with the microfluidic patch and algorithms predicting measured WBSR within 95% LOA of ±0.61 L/hr compared with the reference method. These results are consistent with previous research using the microfluidic device in competitive youth basketball players and extend the validation of the device to elite basketball players. It is also important to note the ecological validity of these results given that the testing took place in uncontrolled conditions. The microfluidic device produced results similar to reference methods during live coach-led practices, despite the presence of arm hair, tattoos, and/or the wearing of shirt sleeves over the patches.

To put these results in practical context, the microfluidic patch WBSR prediction errors were expressed as a percentage of each player’s body mass to show how the over- or underestimation in WBSR could impact fluid balance (if the athlete were to consume the same amount of fluid that the microfluidic patch/app predicted was lost via sweating). As shown in Figure 4b, 98% of the players’ predicted fluid balance was within ±1.0% body mass, thus avoiding significant under- and overhydration (McDermott et al., 2017). For one player the WBSL prediction error was equivalent to +1.5% of body mass. Still, significant overhydration should be avoided in practice if fluid intake plans aim for up to 1% body mass loss. Moreover, it is noteworthy that some of the differences between measured and predicted WBSR could be due to the reference
methods used to measure WBSR in this study. This includes imprecision associated with body mass measurements in the field (e.g., scale sensitivity and trapped sweat in compression clothing) and the crude estimation of nonsweat sources of mass loss.

The microfluidic patch predicted local sweat [Cl\(^-\)] within 10 mmol/L of standard methods for 70% of players and within 20 mmol/L for 95% of players, which is likely sufficient to identify players with high versus lower risk for large sweat electrolyte losses. As discussed previously, the microfluidic patch measures chloride because there is a well-established colorimetric assay for chloride, while no reliable assay is available for sodium. Since most electrolyte replacement guidelines are centered around sodium, the

Figure 2 — Scattergrams showing individual data for LSR (panel a, n = 53) and local sweat chloride concentration (panel b, n = 41) using the absorbent patch and wearable microfluidic device. Separate analyses were conducted to compare the absorbent patch and wearable microfluidic device for subjects with and without tattooed skin on their ventral forearms. Panel c shows LSR (n = 25 with tattoos; n = 28 without tattoos) and panel d shows sweat chloride concentration (n = 19 with tattoos; n = 22 without tattoos). Horizontal line represents the group median, and the plus sign represents the mean. p > .05 for all comparisons of the absorbent patch versus wearable microfluidic device. LSR = local sweating rate.

Figure 3 — Scatterplots of the microfluidic device versus absorbent patch results for LSR (panel a, n = 53) and local sweat chloride concentration (panel b, n = 41). LSR = local sweating rate; CI = confidence interval; Obs = Observed.
smartphone application associated with the microfluidic patch converts local sweat [Cl\(^-\)] to whole-body sweat [Na\(^+\)]. This conversion uses regression equations developed from previously published data demonstrating significant relations between local and whole-body sweat [Cl\(^-\)], and whole-body sweat [Cl\(^-\)] and whole-body sweat [Na\(^+\)] (Baker et al., 2018, 2019, 2020).

It was of interest to determine the potential impact of tattoos on the accuracy of the microfluidic device since some previous studies (Luetkemeier et al., 2017, 2020), but not others (Beliveau et al., 2020; Rogers et al., 2019), have suggested that tattoos may alter LSR and sweat electrolyte concentrations. In the present study, 25 of the 53 players (47%) had a permanent tattoo on at least one of their ventral forearms under the absorbent and/or microfluidic patches. However, there were still no significant bilateral differences in LSR or sweat [Cl\(^-\)] when analyses were conducted separately for the 25 tattooed subjects. These results are consistent with others reporting no effect of tattoos on LSR and sweat electrolyte concentrations during exercise-induced sweating (Beliveau et al., 2020; Rogers et al., 2019) and corroborates the validity of local sweat sampling and analyses from tattooed skin.

While the microfluidic wearable is a valid and practical method for sweat testing in the field, it is not without limitations. As noted in Figure 1, we were unable to obtain viable data from \(n = 11\) subjects for LSR and \(n = 23\) subjects for local sweat [Cl\(^-\)]. One of the most common limitations was the patch becoming unadhered from the arm during high impact aspects of practice (scrimmages). This was a limitation in 14% of players (\(n = 9\)) with the microfluidic patch versus 3% (\(n = 2\)) with the absorbent patch and affected the ability to obtain both LSR and local sweat [Cl\(^-\)]
measurements. This percentage of patch failure was higher than our previous validation study (Baker et al., 2020), but much of the prior testing was conducted in a controlled laboratory setting (cycling), or in the field with individual sports involving no contact (e.g., running, track and field, tennis), or team sports (e.g., soccer) with typically less physical contact than occurs with basketball. Future research is needed to determine if a stronger patch adhesive or application to a different anatomical location may reduce the prevalence of this failure mode for high contact sports such as basketball. The other limitation with the microfluidic patch occurred when sweat did not advance far enough in Microchannel 2 (chloride channel) to initiate the colorimetric reaction. Insufficient sweat volume was a limitation in 19% of players (n = 12) with the microfluidic patch versus 1.5% (n = 1) with the absorbent patch and tended to occur with players who had less practice time on court and lower sweating rates (<0.5 mg-cm⁻²·min⁻¹). This limitation only affected the ability to obtain local sweat [Cl⁻] measurements because sufficient sweat was still collected in Microchannel 1 (volume channel). Future research is needed to address this limitation, perhaps by applying the patch to a location with a higher LSR (e.g., back) during shorter duration exercise or players with lower sweating rates.

There are few descriptive studies on hydration and nutrition behaviors during exercise in elite basketball players (Garth & Burke, 2013). Current guidelines suggest that athletes participating in >1 hr of stop-and-go sports should consume 30–60 g of carbohydrate per hour during exercise (Burke et al., 2011; Thomas et al., 2016). In the present study, 75% of players consumed less than 30–60 g carbohydrate per hour. Nearly a fifth of players (10 out of 53) ingested no carbohydrate at all. For most players in the present study, who drank enough fluid to avoid significant hypohydration, they could consider solid/semisolid forms (gels, chews, and bars) of carbohydrate to increase intake to 30–60 g/hr. By contrast, the 12% of players who accrued significant hypohydration (>2% body mass loss) should be advised to increase their carbohydrate intake through sports drink and/or water plus solid/semisolid carbohydrate sources (Pfeiffer et al., 2010a, 2010b). However, there are potential limitations in interpreting the carbohydrate intake data since the present study was not a game setting and no instructions were given to players. Alternative reasons for not needing/wanting to consume 30–60 g/hr during practice (e.g., significant carbohydrate intake before exercise or players attempting to reduce caloric intake to lose weight) cannot be ruled out.

In conclusion, the wearable microfluidic device and smartphone application algorithms provide similar LSR, local sweat [Cl⁻], and WBSR results compared with the standard field-based methods in elite male basketball players, with or without tattooed skin, during typical moderate-intensity practice sessions that include a mix of noncontact drills and live high contact scrimmages. With respect to hydration and nutrition behaviors, only 12% of players accrued >2% body mass loss, while 75% of players did not meet the carbohydrate intake recommendations (30–60 g/hr) during practice. More research regarding carbohydrate intake of elite athletes during basketball training is needed.

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