Carbohydrates in sports nutrition

Position of the working group sports nutrition of the German Nutrition Society (DGE)

Daniel König, Hans Braun, Anja Carlsohn, Mareike Großhauser, Alfonso Lampen, Stephanie Mosler, Andreas Nieß, Helmut Oberritter, Klaus Schäbethal, Alexandra Schek, Peter Stehle, Kiran Virmani, Rainer Ziegenhagen, Helmut Heseker

Abstract

Carbohydrates are an important source of energy during physical exercise. Carbohydrates lead to a higher energy yield and higher energy flux per liter of oxygen than the oxidation of fatty acids. However, the storage capacity for carbohydrates in liver and muscles is limited. Therefore, endurance athletes should include a high proportion of carbohydrates in their daily diet. The individual amount depends on body weight and the extent of physical activity. Energy expenditure during physical exercise results in a gradual depletion of carbohydrate stores. The extent to which carbohydrate stores are depleted is dependent on the duration and intensity of exercise. Therefore, in particular during prolonged intense exercise, performance may be improved by consuming an adequate amount of carbohydrates during exercise. In addition, following a long period of intensive physical activity, rapid post-exercise intake of carbohydrates can help replenish carbohydrate stores more quickly.

This position paper sets out current guidelines for the type, amount and timing of carbohydrate intake in sport. It will also discuss the significance of "carbohydrate loading", the glycemic index, and training without prior intake of carbohydrates.

Keywords: carbohydrates, position statement, sports nutrition, glycogen stores, energy supply

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Introduction

Among macronutrients, carbohydrates are particularly important for athletic performance [1]. Carbohydrates have a very high energy efficiency and can be metabolized both aerobically and anaerobically [2]. Particularly when oxygen uptake is considered, which is particularly important in endurance sports, the energy yield in terms of the amount of adenosine triphosphate (ATP) per liter of oxygen is higher for carbohydrates than for fatty acids [3].
The total energy yield during anaerobic (2 Mol ATP/Mol glucose) and aerobic (36 Mol ATP/Mol glucose) glucose metabolism is less than for the metabolism of fatty acids (e.g. 122 ATP/Mol stearic acid), but the flux of energy, i.e. the ATP yield per unit of time is much higher for carbohydrates [4].

Compared to energy yield from fatty acids, ATP resynthesis/unit of time is twice as high for aerobic metabolism of glucose. In the case of anaerobic metabolism of glucose, this value is actually four times higher [5].

Therefore, it has been shown that a high proportion of carbohydrates in the diet can significantly improve physical performance during prolonged, intense physical exercise [6]. Furthermore, there is increasing evidence that the level of carbohydrate stores in the liver and muscles affects training-induced adaptation processes in the body [1, 7, 8].

The importance of carbohydrate intake for athletic performance will be demonstrated below with reference to the following aspects:
- Carbohydrates in the period before physical exercise
- Carbohydrates during physical exercise
- Carbohydrates in the period immediately after physical exercise

Carbohydrate consumption	Exercise intensity	Intake level
low	low intensity	3–5 g/kg BW/d
moderate	moderate exercise (approx. 1 hour of moderate training per day)	5–7 g/kg BW/d
high	competitive endurance training (moderate to high-intensity training for 1–3 hours per day)	6–10 g/kg BW/d
very high	extreme training exercise (moderate to high-intensity training for 4–5 hours per day)	8–12 g/kg BW/d

Tab. 1: **Daily intake for carbohydrates in dependence of exercise intensity [1]**
d = day; BW = body weight

Carbohydrates in the period prior to exercise

Daily nutrition

The basis of the athlete's diet is food that provides all necessary nutrients in accordance with the food-based dietary guidelines of the German Nutrition Society *(Deutsche Gesellschaft für Ernährung, DGE)* [9, 10]. One of the key reasons for the focus on carbohydrates in the basic diet of endurance athletes is the fact that carbohydrates are optimal for restoring glycogen stores in the liver and muscles [1, 11, 12]. Muscle biopsy studies have shown that a high proportion of carbohydrates in the diet is also associated with high hepatic and muscular glycogen stores. In addition, the level of glycogen stores correlated relatively closely with the subsequent duration of exercise in endurance tests to exhaustion [6].

Compared to fat stores in the human body (approx. 80,000–100,000 kcal), glycogen stores in the muscles (approx. 1,230–2,050 kcal) and the liver (approx. 410 kcal) are limited. If glycogen stores are depleted, energy can no longer be provided by carbohydrates. Consequently, because the ATP yield per unit of time is smaller for the oxidation of fatty acids (see above), exercise intensity must be reduced.
The rate of glycogen depletion depends on the duration and intensity of exercise; in addition, glycogen depletion is dependent on the total amount of glycogen that can be stored and on how much the stores are filled at the beginning of exercise [8]. In the case of intense endurance exercise within the range of the anaerobic threshold, the energy that is stored in fully replenished glycogen stores is sufficient for an exercise duration of approx. 75–90 minutes; incompletely filled glycogen stores are associated with a correspondingly lower exercise duration [8, 11, 13].
Therefore, athletes who are training or competing on a regular basis should consider a sufficient amount of carbohydrates in their diet.

♦ Table 1 shows differences in the amount of carbohydrate intake as a function of duration of training and exercise intensity, published by the American College of Sports Medicine (ACSM) [1].
The exact amount of carbohydrates to improve performance in different types of sports is still under debate [1, 6, 7, 14]. Particularly when looking at different carbohydrate regimes during training sessions, there are currently various concepts for modifying carbohydrate intake with the aim of potentially improving performance. One of the most topical at the moment is training with low glycogen stores ("train low") to improve fat oxidation (see also "Position statement of the working group sports nutrition of the German Nutrition Society (DGE): Fats in sports nutrition" [15]) [14, 16, 17].

Glycogen availability is very likely modulated by signaling proteins that are activated by physical training such as AMP-activated protein kinase (AMPK) or p38 mitogen-activated protein kinase (MAPK) [1, 18]. Both AMPK and MAPK are involved in the regulation of the expression and activity of transcriptors and transcriptional coactivators, which influence mitochondrial biogenesis and therefore oxidative capacity [19].
Although many studies have demonstrated an improvement in oxidative capacity after a training phase with low or empty glycogen stores, it has not yet been conclusively shown whether this has medium-term or long-term consequences for competition performance [14, 16]. Training with low or empty glycogen stores may negatively affect performance by downregulating glucose transporters (GLUT-4) [17]. However, in the case of highly intense endurance competitions, it is not possible to succeed without carbohydrates as an energy source; furthermore, regarding training periodization, the optimal timing to increase the amount of carbohydrate intake again has not been established [1, 7, 14].

Also the glycemic index is relevant with regard to the metabolic effects of a carbohy-

drate-rich diet in sports. The glycemic index describes the increase in blood glucose after the intake of carbohydrate containing meals compared to the intake of a standard comparative food, such as white bread or glucose solution. In addition to the increase in blood glucose, the postprandial increase in insulin levels is also dependent on the glycemic index [20].
The blood insulin level plays a key role in the regulation of carbohydrate oxidation versus fat oxidation [21]. A high glycemic index is associated with a high postprandial insulin level which in turn leads to a lower fat oxidation [22, 23]. This association has also been demonstrated in athletes during physical exercise [24]. However, whether carbohydrates with a low glycemic index can also improve endurance capacity following training is currently under debate [25, 26].

Carbohydrates before competition

If the competition lasts less than 90 minutes, no change in the daily intake regime shown in ♦ Table 1 is currently recommended [1, 23]. If the competition lasts more than 90 minutes, an increase in carbohydrate intake in the days before competition has often shown to improve performance [27].
Strategies to further increase glycogen stores are known as carbohydrate loading or "supercompensation". Currently, carbohydrate loading can be recommended for a competition duration of more than 90 minutes.
The method of carbohydrate loading that is most common at the moment involves a relatively high increase in carbohydrate intake of 10–12 g carbohydrate/kg of body weight per day (kg body weight/d) for a period of 36–48 hours prior to competition. This can further increase glycogen concentration in the muscles by approx. 10–15% and allows carbohydrate oxidation to be maintained longer during endurance exercise. Another method for carbohydrate loading consists in increasing carbohydrate intake in the week prior to a competition (e.g. 9–10 g carbohydrate/kg body weight/d) with simultaneous reduction in the extent and intensity of training.
A further method involves intensive, glycogen-depleting endurance exercise 72 hours prior to the competition. The prior exercise is intended to upregulate the activity of GLUT-4-transporters and glycogen synthase, which should also lead to a supramaximal filling of glycogen stores in the subsequent days until competition when further supported by a carbohydrate-rich diet (e.g. 9–10 g carbohydrate/kg body weight/d).

It is not advised to test out different methods for carbohydrate loading before an important competition. Not all athletes can tolerate very large quantities of carbohydrates and it is not advisable to risk compromising performance in important competitions due to gastrointestinal problems. It is often stated that athletes should train the gastrointestinal system in order to deal with a high carbohydrate intake. However, further research is required to investigate the extent to which this is necessary, feasible and tolerable [28].

Nutrition on the day of competition

It is recommended that endurance athletes should consume a carbohydrate-rich meal (1–4 g carbohydrate/kg body weight, depending on the duration and intensity) 2–3 hours before a competition when exercise duration exceeds 60 minutes [1]. This replenishes glycogen stores in the muscles and particularly in the liver, which could already show a significant overnight reduction in glycogen levels [7]. Many albeit not all studies have demonstrated that a carbohydrate-rich meal prior to exercise leads to an improvement in performance [1].
The recommendation to consume the pre-exercise meal 2–3 hours before the start of competition is based on the fact that by then the feeling of fullness is reduced and the postprandial hormonal response has largely returned to baseline. Following a carbohydrate-rich pre-exercise meal, metabolism of carbohydrates is increased and fat oxidation is simultaneously decreased because lipolysis and fat oxidation are already inhibited by relatively small amounts of insulin in the blood. However, the higher proportion of carbohydrates that is now being metabolized is fully compensated by the higher amount of carbohydrates ingested by the carbohydrate-rich meal. Therefore, although carbohydrate oxidation is increased this is not associated with a quicker depletion of glycogen stores. In the case of a very short pre-exercise interval of less than 60–90 minutes, blood glucose concentrations, and particularly insulin concentration remain relatively high at the start of exercise. This induces a pronounced increase in carbohydrate metabolism in skeletal muscles that can be desirable for shorter, more intensive periods of exercise within the range of the anaerobic threshold. For long endurance distances in a rather moderate intensity range (60–70% VO_2max[1]), however, a higher metabolic proportion of fat is preferable, as this also protects the glycogen stores. For this reason, the interval between the intake of food and the start of the competition should be selected in such a way that the initial digestive phase is completed and the insulin concentration has returned largely to the fasting range.

[1] VO_2max: maximal O_2 uptake from inhaled air per unit of time during maximum exertion.

The glycemic index of the meal eaten prior to exercise can also affect substrate oxidation during exercise. Studies have shown that a pre-exercise meal with a low glycemic index leads to increased fat oxidation during the subsequent exercise [24, 29]. This means that due to lower insulin concentration, fatty acids are metabolized preferentially over carbohydrates at the same intensity of exercise. A possible advantage of this would be that the glycogen stores are conserved during longer periods of exercise requiring endurance due to the relatively higher proportion of fatty acids used in energy production.
However, the statements that have been made regarding the effects and significance of the glycemic index in the pre-exercise phase are contradictory. Depending on the studies included and the test algorithm chosen, the meta-analysis by Heung-Sang et al. comes to the conclusion that a low glycemic index in pre-exercise meal provides a performance advantage [26], whereas the meta-analysis by Burdon et al. showed no significant difference [25].

Carbohydrate intake during physical exercise

General recommendations

In most studies, continuous carbohydrate intake during intensive, long-lasting exercise maintained the oxidation of carbohydrates and thus prevented hypoglycemia and in turn prevented termination of exercise [30]. In addition, the immediate involvement of orally administered carbohydrates in energy metabolism during exercise was demonstrated using labeled glucose. Furthermore, systematic reviews and meta-analyses have confirmed that the exercise time that can be achieved is extended significantly by continuous carbohydrate intake during exercise [1, 6].
Extended performance through carbohydrate intake is attributable, among other factors, to conservation of glycogen in the muscles, conservation of hepatic glycogen stores, the prevention of hypoglycemia, and the maintenance of a high energy flow rate [1, 7, 8, 31]. The conservation of glycogen stores in the liver is particularly important during exercise involving intensive "final spurts", as these hepatic glycogen stores can still be used as a "final reserve" towards the end of a high-intensity exercise [27, 32, 33].

For practical reasons, during exercise, carbohydrates are usually consumed in the form of drinks. It is currently recommended that, depending on the intensity of exercise, individual tolerance and climatic conditions, 150–350 ml of a drink with a carbohydrate concentration of approx. 6% should be drunk every 15 minutes for a duration of more than 60 minutes [34].
Frequently, athletes ask whether certain forms of carbohydrate administration (e.g. drink, bar, or gel) have different effects on the speed of carbohydrate oxidation during exercise. Although carbohydrates are certainly available more quickly in liquid form, it does not seem to play a role during prolonged exercise performance in which dosage form the carbohydrates are supplied. Here, athletes can follow their personal preferences [35]. However, it should be noted that extra care must be taken to ensure a sufficient intake of fluids so that the passage through the stomach is not delayed and the osmotic load is not too high.

The oxidation rate of exogenously supplied glucose during exercise is approx. 1–1.2 g/min and cannot be further increased through a higher glucose or maltodextrin intake. During submaximal exercise, the limiting factor is the absorption in the small intestine rather than the gastric emptying rate [28]. In fact, glucose transport proteins in the small intestine have a capacity limit. However, studies have shown that different carbohydrates taken up by different carrier systems lead to increased absorption and thus increased carbohydrate oxidation. Therefore, a combination of glucose, fructose and sucrose, respectively, increased the oxidation rate to values of 1.5-1.7 g/minute [11, 23].

From the current literature, it can be deduced that the use of different carbohydrates with different transport mechanisms could be useful, especially in the case of extremely intensive endurance stress over 2.5 hours [36, 37]. However, it has to be pointed out that athletes often cannot tolerate such large amounts of carbohydrates during physical exercise. It is often reported that the intake of large amounts of carbohydrates can be trained; this must be tested individually [28]. Since many preparations containing carbohydrate mixtures contain fructose, fructose intolerance must be excluded in advance, otherwise negative effects on performance can be expected.

In recent years, there has been much speculation as to whether the additional administration of protein in the form of a carbohydrate-protein mixture can improve performance even further. The number of studies on this is rather sparse [38]. However, there is a broad consensus that when glucose intake is adequate, the addition of extra protein does not have any performance-enhancing effect [13]. Some studies demonstrated that the intake of a carbohydrate-protein mixture led to a reduction in the release of muscle enzymes (e.g. creatine kinase) and decreased muscle fatigue [38, 39]. Even so, the relevance of these findings in terms of endurance and success of training is uncertain. Therefore, when carbohy-

Duration of exercise	Carbohydrate intake amount	Type of carbohydrate	Recommendations
< 45 minutes	not needed		
45–75 minutes	small amounts or possibly mouth rinsing	individual monosaccharides or a combination of monosaccharides that are absorbed via various carrier systems (e.g. Gluc/Frc)	
1–2.5 hours	approx. 30–60 g/h	individual monosaccharides or a combination of monosaccharides that are absorbed via various carrier systems (e.g. Gluc/Frc)	testing and if appropriate, "training" recommended
> 2.5 hours	up to 90 g/h	combination of monosaccharides that are absorbed via various carrier systems (e.g. Gluc/Frc)	testing and if appropriate, "training" essential

Tab. 2: **Carbohydrate intake levels recommended by the ACSM during intensive physical exercise (mod. according to [1])**
ACSM = American College of Sports Medicine; Frc = fructose; Gluc = glucose; h = hour

drate intake is sufficient to cover needs, there is no discernible additional benefit of protein intake during endurance exercise [38].
♦ Table 2 shows the recommended carbohydrate intake levels during athletic activity as a function of duration of exercise and exercise intensity.

Stimulation of the central nervous system through carbohydrates

A limited energy supply and thus a reduced blood glucose concentration can contribute to central fatigue. It has been claimed – among other things – that an increased serotonin concentration in the central nervous system (CNS) is involved [40]. However, there is no clear evidence of an effect on any particular cerebral metabolic pathway that is relevant to performance [41]. Nevertheless, studies have demonstrated that simply rinsing the mouth with drinks containing carbohydrates can have a positive effect on performance, especially in the case of short exercise bouts lasting 30 to 60 minutes [42]. This effect is triggered by stimulation of oral carbohydrate receptors and it promotes performance via CNS activation of reward centers with subsequent stimulation of motor neurons [43]. These studies are particularly interesting from a physiological point of view in terms of better understanding the effects of carbohydrates for short periods of exercise as well. It could not be demonstrated that there was any additional benefit of mouth rinsing alone compared to rinsing and subsequent swallowing. From an athlete's point of view, these findings probably only have practical relevance in terms of carbohydrate intolerance before exercise or competitions.

Carbohydrate intake in the period immediately after exercise

Following exercise, both the amount and timing of carbohydrate intake play an important role in fast and complete replenishment of glycogen stores. Carbohydrate intake immediately after intensive exercise leads to higher glycogen resynthesis than a comparable amount of carbohydrate consumed 2 hours later. This is attributable to contraction-induced increased expression of GLUT-4 and glycogen synthase in the skeletal muscle cells [44]. After this initial time window with a higher synthesis rate, glycogen synthesis is insulin-dependent and slower [44, 45].
The extent to which these two phases can be differentiated from each other physiologically has not been clearly demonstrated. Because postprandial insulin concentration correlates closely with the glycemic index, consuming carbohydrates with a high glycemic index is recommended in the period immediately after exercise [46].
It is therefore recommended to consume approx. 1–1.2 g carbohydrate/kg body weight/h in the first 2–4 hours after the end of exercise [1]. Quantities of carbohydrate higher than this do not lead to any significant additional increase in glycogen resynthesis. However, this effect is only significant if there are less than 8–10 hours between the end of exercise and the start of the next exercise session. If the interval between two competitions or training sessions is longer, it appears that if carbohydrate intake is adequate, the timing of intake does not affect the extent of glycogen resynthesis after 24 hours [1].

Therefore, it is broadly accepted that carbohydrates should be available as quickly as possible in the period immediately after ex-

Situation		Carbohydrate intake
daily filling of glycogen stores	preparation for exercise/ competitions lasting < 90 minutes	7–12 g/kg BW over the course of 24 hours
carbohydrate loading	preparation for exercise/ competitions lasting > 90 minutes	over the course of 36–48 hours 10–12 g /kg BW over the course of 24 hours
pre-exercise meal	prior to exercises lasting > 60 minutes	1–4 g/kg BW (consumed 2–3 hours prior to exercise)
short periods of exercise	< 45 minutes	not needed
high-intensity exercises	45–75 minutes	small amounts (possibly mouth rinsing)
exercises requiring endurance (including intermittent exercise)	1–2.5 hour(s)	30–60 g/h
ultra endurance events	2.5–3 hours or longer	up to 90 g/h with combined carbohydrates
rapid replenishment of glycogen stores	< 10 hours pause between 2 intensive, long-lasting periods of exercise requiring endurance	1–1.2 g/kg BW every hour after the end of exercise for a duration of 4 hours

Tab. 3: **Summary of intake recommendations for carbohydrates [1]**
h = hour; BW = body weight

ercise and that they should have a high glycemic index. According to current research, the combination of glucose and fructose does not increase glycogen resynthesis because the glycemic index of fructose is too low and therefore the lower insulin release does not contribute to an increased rate of resynthesis [47].

In analogy to the combined supply of carbohydrates and proteins during exercise, it has long been discussed whether such a combination may be beneficial in the post-exercise period. The main aim of a combined intake of carbohydrates and proteins would be to optimize glycogen resynthesis. However, results from controlled studies vary depending on the timing and amount of such a combined intake. The current findings suggest that with a carbohydrate intake of approx. 1.2 g/kg body weight/h in the post-exercise phase, proteins cannot be expected to have any additional positive effect on glycogen stores. If, for reasons of training methodology or gastrointestinal intolerances, the carbohydrate quantity needs to be lower than 1.2 g/kg body weight/h, then glycogen stores can be better replenished by the addition of proteins than with a carbohydrate quantity of less than 1.2 g/kg body weight/h alone [27].

A recent meta-analysis investigated the possible additional benefit of combined carbohydrate and protein administration in the case of only a short interval between two exercise sessions. The authors concluded that intake of carbohydrates in the post-exercise phase is relevant with regard to performance and that simultaneous protein intake does not yield any additional benefits [13].

Summary

Depending on the duration and intensity of exercise, a carbohydrate intake of 6–12 g carbohydrate/kg body weight/d is recommended for endurance athletes [1].

This recommendation is based on the following basic considerations (see also ♦ Table 3):

1. The use of carbohydrates results in a higher energy flux and an increased energy yield/liter of oxygen in the muscles than when fats or proteins are utilized. Prolonged endurance exercise (> 75–90 minutes) in the range of approx. 70–75% VO_2max are therefore only possible with a high proportion of carbohydrates contributing to muscular energy supply.
2. The level of the glycogen stores in the liver and the muscles (approx. 1,600–2,400 kcal) is limited. A carbohydrate-rich diet in the period prior to exercise ensures optimal filling of muscular and hepatic glycogen stores between training sessions or between competitions.
3. Intermittent intake of carbohydrate-rich drinks or snacks can maintain energy supply from carbohydrates even in the case of prolonged endurance exercise. Increased muscular metabolism of exogenously supplied glucose during exercise can significantly extend exercise duration. The oxidation rate of exogenously supplied glucose during exercise is approx. 1–1.2 g/min and cannot be further increased through a higher glucose or maltodextrin intake. The limiting factor is the absorption rate in the small intestine. The consumption of different carbohydrates that are absorbed via different carrier systems can result in increased absorption and

thus increased carbohydrate oxidation (1.5–1.7 g/min). However, these measures are only necessary in the case of long and intensive endurance exercise.

4. Particularly in the case of repeated exercise sessions with a short interjacent interval, 1–1.2 g of carbohydrate/kg body weight/h (ideally carbohydrates with a high glycemic index) should be consumed in the phase immediately after exercise, i.e. the first 2–4 hours, in order to ensure rapid replenishment of glycogen stores. If there is a longer interval between exercises, 6–10 g carbohydrate/kg body weight/d is sufficient to replenish glycogen stores. With regard to glycogen resynthesis, additional administration of proteins is only useful if less than 1.2 g carbohydrate/kg body weight/h is consumed.

Corresponding author
Klaus Schäbethal
schaebethal@dge.de

Prof. Dr. Daniel König[1]
Hans Braun[2]
Prof. Dr. Anja Carlsohn[3]
Dr. Mareike Großhauser[4]
Prof. Dr. Dr. Alfonso Lampen[5]
Dr. Stephanie Mosler[6]
Prof. Dr. Andreas Nieß[7]
Dr. Helmut Oberritter[8]
Klaus Schäbethal[8]
Dr. Alexandra Schek[9]
Prof. Dr. Peter Stehle[10]
Dr. Kiran Virmani[8]
Dr. Rainer Ziegenhagen[5]
Prof. Dr. Helmut Heseker[11]

[1] Institut für Sport und Sportwissenschaft
Arbeitsbereich Ernährung
Albert-Ludwigs-Universität Freiburg
[2] Institut für Biochemie
Deutsches Forschungszentrum für Leistungssport – momentum; Deutsche Sporthochschule Köln
[3] Fakultät Life Sciences/Department Ökotrophologie
Hochschule für Angewandte Wissenschaften Hamburg
[4] Olympiastützpunkt Rheinland-Pfalz/Saarland
[5] Abteilung Lebensmittelsicherheit (Abt. 5)
Bundesinstitut für Risikobewertung (BfR)
[6] Institut für Gesundheitswissenschaften
Abteilung Ernährung, Konsum und Mode
Pädagogische Hochschule Schwäbisch Gmünd
Olympiastützpunkt Stuttgart
[7] Abteilung Sportmedizin
Medizinische Klinik
Universitätsklinikum Tübingen
[8] Deutsche Gesellschaft für Ernährung e. V. (DGE)
[9] Redaktion Leistungssport (DOSB)
[10] Institut für Ernährungs- und Lebensmittelwissenschaften
Ernährungsphysiologie
Rheinische Friedrich-Wilhelms-Universität Bonn
[11] Institut für Ernährung, Konsum und Gesundheit
Fakultät für Naturwissenschaften Universität Paderborn

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Conflict of Interest
The authors declare no conflict of interest.

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