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Ketogenic Diets Are Not Beneficial for Athletic Performance

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We write as sports scientists who support elite endurance athletes, defining endurance sports as competitions of >30 min duration where success is determined by an athlete's ability to sustain the highest power outputs/speed, for the event duration or at critical moments. Although many factors contribute to performance, the availability of muscle fuels and integration of their optimal use have dominated sports nutrition interests for a century (1). Unsurprisingly, endurance athletes have focused on key attributes of carbohydrate (CHO) metabolism: its rapid activation, provision of an oxygen-independent pathway for adenosine triphosphate (ATP) production, and a 5-7% greater ATP yield per L of oxygen consumed in its oxidative pathway compared with fat (2). Therefore, the ground-breaking 1983 paper by Phinney et al. (3) demonstrating that massive reserves in muscle capacity for fat oxidation, even in endurance-trained athletes, could be unlocked by 4-weeks of ketogenic low-CHO high-fat (LCHF) intake, challenged contemporary beliefs about the absolute importance of muscle glycogen utilization during prolonged moderate-intensity exercise. Curiously, there was no association between the improvements in exercise capacity and the increase in fat oxidation (glycogen sparing) in these cyclists (3), suggesting other explanations for the observed changes in endurance; these include day to day variability and training-induced changes that were amplified by the order effect in the study protocol (all cyclists undertook the LCHF trial as their second trial). Most importantly, however, we were unable to find a home for this strategy within our domain, due to the coincidental discovery that "...the price paid for the conservation of CHO during exercise appears to be a limitation of the intensity of exercise that can be performed…. a throttling of function near $\dot{V}O_{2max}$" (3).

Thirty years later, when social media and hypothesis created #LCHF, we were sufficiently intrigued and motivated to collaborate with world-class endurance athletes to ensure we hadn't missed anything from earlier work (4). Although expenditure of blood, sweat and tears, in the lab and field, has unearthed new knowledge (5), we are still unable to find a place for "keto-adaptation" among our high performance athletes. Ketogenic diets merit wider discussion in other forums and with other forms of sport, but here we consider substrate use and performance in endurance-trained athletes, with brief recognition of: (a) potential Black Swans that challenge these understandings; and (b). the importance of understanding the limitations of measurement techniques and evidence sources.

Substrate Use and Economy

The gold standards for determining substrate utilization during exercise involve the use of stable isotopes and/or skeletal muscle biopsies. Such work, performed in both aerobically trained men (6, 7) and women (8), has demonstrated that maximal rates of fat oxidation occur at ~55-65% $\dot{V}O_2$, with an increased reliance on blood glucose and muscle glycogen at higher intensities. Meanwhile, there is strong evidence from studies using indirect calorimetry to assess substrate utilization that adherence to a LCHF (<50 g/d CHO, 75-80% energy from fat) diet achieves substantial (~200%) increases in maximal rates of fat oxidation during exercise, up to ~1.5 $g \cdot min^{-1}$ at ~65-70% of $\dot{V}O_{2max}$ and up to 2 g min^{-1} in individuals (9-11). Although early studies (3) and lay promotion (12) identified that a 3-4 week period was able to maximize fat oxidation and restore perceived exercise exertion, key changes in muscle glycogen and fat utilization likely occur within 5-10 d of fat-adaptation (13). Regardless, in our hands, peak fat oxidation in elite and world class athletes occurs at ~67% of $\dot{V}O_{2max}$ even after adaptation to a LCHF diet (see

Figure 1), which is consistent with previous studies utilizing tracer methodology.

While these findings don't negate the opportunity for increased rates and contribution of fat oxidation to fuel use at higher exercise intensities compared with CHO-adapted conditions, both the validity of these estimated rates and the effect on performance need to be considered. The use of indirect calorimetry to determine substrate oxidation relies on athletes being in a metabolic steady-state, as changes in the bicarbonate pool can artificially increase $\dot{V}CO_2$. The accuracy of this methodology at higher intensities (i.e., >70-85% $\dot{V}O_{2max}$) has therefore been questioned (14, 15). While it could be argued this would only underestimate fat oxidation rates, at higher intensities, additional factors including uncoupling of mitochondrial respiration (16) may result in increased $\dot{V}O_2$, particularly in lower caliber athletes who are unfamiliar or unable to maintain such paces.

Claims that substrate utilization and performance optimization require lengthier adaptation (>3-4 months) are largely unstudied. However, cross-sectional observations of long-term (>6 months) keto-adapted athletes typically report similar muscle fuel use characteristics to 3-4 w interventions (11, 17). A curious finding of normalized glycogen storage with a non-oxidative fate during running in long-term keto-adapted athletes (11) merits further investigation. Until such time, we suggest this is an artefact caused by glycogen measurement issues rather than a Black Swan. Indeed, it contradicts findings from a similar study of cyclists (17) and within the same investigation, post-exercise glycogen storage rates in the control (higher-CHO) group were extreme outliers, with ten-fold higher rates than reported in a multitude of other studies (5).

Performance

At the risk of being considered elitist, and notwithstanding the much larger number of recreational athletes who participate in sporting events (18, 19), the benchmark for considering sports performance should involve considerations for true high-performance athletes. Furthermore, priority should be given to protocols that measure performance with ecological validity and with sufficient sensitivity to detect changes with real world significance. In general, adaptation to LCHF can preserve capacity for moderate-intensity (60-70% $\dot{V}O_{2max}$) exercise (3, 20), although considerable individual responsiveness to LCHF is demonstrated by variability in exercise capacity/performance outcomes (3, 20) and large rates of study withdrawal/inability to maintain compliance (21). However, it is the compromised performance in higher-intensity domains (>80% $\dot{V}O_{2max}$), identified in the original study (3) and demonstrated in real world circumstances (9, 10, 13, 22) that is of greatest relevance to high performance endurance athletes. In our hands, four studies (9, 10, 13, 22) involving different but carefully implemented permutations of ketogenic LCHF diets, underpinned by guidelines from its original supporters (12), have found remarkably consistent performance impairments in sanctioned races (Figure 1). This mirrors the loss of exercise economy (higher oxygen cost) seen in complementary testing in our studies (9, 10, 13, 22) and by other groups (20), and predicted by fundamental stoichiometry. Economy changes within the same athlete are associated with critical changes in race speed and can significantly impact performance outcomes. For example, the carbon-fiber plated running shoes implicated in the recent improvement of every world record from 5-km to the marathon mprove economy by ~4% (23); this is of similar magnitude to the *impaired* economy seen with keto-adaptation.

Studies of keto-adaptation and performance in competitive athletes require substantial resources, attention to compliance/supervision and methodological rigor, and enormous collaboration with the participants. Although, our endeavors have been admired, we respond to criticisms that our studies are flawed by the allocation of treatments according to positive belief effects rather than random assignment (24), by noting that expecting elite athletes to compete in real-life races using strategies that they consider sub-optimal is both unethical and unwise (true performance efforts require a full psychological commitment). We note that other studies and individual case histories have challenged the notion of performance limitations with LCHF. Confounding variables in these studies (e.g., weight loss, changes in training load and quality) reduce our ability to attribute performance outcomes to keto-adaptation *per se*, just as they do with real-life "anecdata". Indeed, although photos of meals or comments about isolated dietary practices by elite athletes are triumphantly paraded by members of dietary religions as evidence of the superiority of their brand, it is neither possible to gain the true picture of an individual's nutritional practices from isolated meals or self-reports nor attribute their sporting success to such glimpses.

Protocols that try to measure exercise metabolism and performance at the same time rarely achieve excellence (and, sometimes, even acceptable practice) in either metric. Measurements of blood, respiratory gas and effort can interfere with assessment of exercise capacity, let alone real-world performance, while the non-steady state or high intensity conditions associated with performance simulations conflict with fundamental principles of measuring substrate utilization and exercise metabolism. For example, male runners ($\dot{V}O_{2max}$: ~61 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) demonstrated impaired 5-km treadmill time trial (TT) performance after 4-d LCHF, but no differences compared to a CHO-rich diet after 14, 28 and 42 d (19). The distance was completed in ~20 min, at speeds equivalent to ~82% $\dot{V}O_{2max}$, apparently contradicting our contention that keto-adaptation impairs capacity for higher-intensity endurance exercise. However, we note that the reported absolute speed and relative fractional oxygen utilization (higher, as predicted, in the LCHF trial) are lower than expected, based on data from other studies of 5-km performance in active males (25), perhaps reflecting a disconnect between real-life performance and treadmill running with continuous gas collection.

More recently, this same approach has been employed to evaluate the effects of LCHF on repeated sprint (6 x 800m) and 1 mile (1609m) TT performance in middle-aged trained males (26). The authors found significant increases in rates of fat oxidation but did not detect differences in the time to complete the sprints or mile TT between treatments. These findings were claimed to refute previous reports that LCHF is incapable of supporting high-intensity exercise. However, it is unclear how indirect calorimetry would account for the anaerobic contribution of the 800m reps, or indeed of the mile time trial. Elite athletes typically race the 1500 m/mile at a velocity corresponding to 105-115% $\dot{V}O_{2max}$, with an estimated 77-85% of energy produced aerobically (27). Yet, the study athletes completed their TT at ~86% $\dot{V}O_{2max}$, likely reflecting both the artificial nature of the test and the relatively lower training status of the participants. It is unlikely that steady-state was achieved at this intensity, questioning the validity of the calculated values as outlined above. Despite this, the authors reported that peak fat oxidation occurred at ~86% of $\dot{V}O_{2max}$. However, even in world-class marathon runners, lactate threshold occurs at ~83% $\dot{V}O_{2max}$, while race pace or sustainable $\dot{V}O_2$ is closer to 86-90% for an event lasting ~2 h (28). This, again, suggests a misunderstanding of the energetics of elite endurance sport, and doubt that fat oxidation can support the rates of energy production needed for success within it.

Can limitations of LCHF be rescued?

Integration with sessions/periods of high CHO availability or other exogenous fuels may rescue the impairment of higher-intensity exercise associated with LCHF alone, allowing keto-adapted athletes to complete high quality training sessions or restore optimal competition performance. We have tested a variety of models, without success in overcoming the performance impairments of LCHF; these include periodized LCHF prior to CHO-supported taper and race preparation (9), restoration of endogenous and exogenous CHO availability via CHO-loading and peri-event CHO intake (13), and pre-race use of exogenous ketone esters (22). A key problem is that fat-adaptation is associated with down-regulation of key enzymes promoting glycogenolysis and commitment of CHO to oxidation pathways (29). This persists in the face of acute restoration of muscle glycogen, continuing to limit the contribution of CHO as a race fuel and the performance of higher-intensity exercise (13). A case history involving an elite keto-adapted triathlete provides the only evidence of a successful integration. Here, consuming CHO during high-intensity training sessions and subsequent performance tests was associated, as predicted by our commentary, with better performance of exercise reliant on higher rates of CHO oxidation but minimal effect on lower-intensity (<60-65% $\dot{V}O_{2max}$) and supra-maximal (>$\dot{V}O_{2max}$) exercise (30). Unfortunately, mechanisms (central nervous system vs. muscle effects; acute benefits vs training support) could not be discerned, and there was no comparison to performance supported by chronic high CHO availability.

Final thoughts from the coal face of elite endurance sport

Endurance athletes who are contemplating keto-adaptation should audit the requirements of their event, balancing: contribution of higher-intensity exercise to their goals; their capacity to maintain adequate CHO availability throughout the event to meet reliance on CHO fuels; whether LCHF could address unavoidable carbohydrate depletion or unwillingness to consume sufficient CHO; and whether their individual responsiveness to keto-adaptation can support performance characteristics. The beauty of sport is its nuances, and we note that two athletes of different caliber, even in the same race, may be undertaking a different event in terms of relative intensities, opportunities for nutrition support and characteristics of success (31).

Therefore, however instructive, the requirement of Perspective to “choose a side” reflects a frailty of our current world; the promotion of binary thinking over nuance, context and complexity. Forced to choose, we agree that keto-adaptation can be a disabler of endurance performance. A fairer world would support several truths: it depends; there’s more to learn; and collaboration beats conflict in expanding knowledge and practice.

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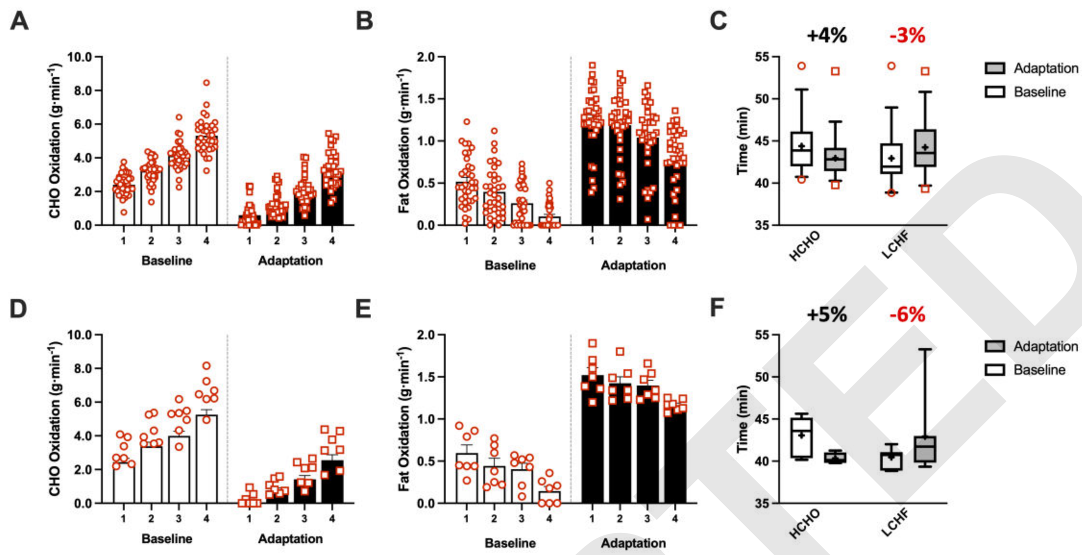
FIGURE LEGEND

Figure 1. Pooled data from Supernova studies assessing changes in calculated substrate utilization and 10,000m race performance in elite and world-class race walkers. Athletes performed a four-stage incremental speed economy test on a treadmill and competed in a World Athletics sanctioned 10,000m track race at baseline and following adherence to a low-carbohydrate, high fat (LCHF) or ketogenic diet. Dietary interventions ranged from 7-days to 3.5 weeks. Panels A-B represent 35 data sets from 29 individuals who adhered to a LCHF or ketogenic diet. Panel C displays the race performance results from those studies, including the control groups who adhered to either a high or periodized carbohydrate/ availability diet (HCHO; 41 data sets from 31 individuals). Bold numbers represent change in finishing time. Panels D-E represent a subset of the athletes who followed a LCHF or ketogenic diet and have won either Olympic or World Championship medals (7 data sets from 4 athletes). Race performance in panel F is compared to medal-winning athletes who participated in the studies and consumed a HCHO diet (6 data sets from 4 individuals). Combined – the athletes tested on a LCHF or ketogenic diet have won 36 medals at Olympic, World, or Area (e.g., European, Asian, Pan American) Championships, and have won over 60 national titles. These studies demonstrated that despite robust retooling of skeletal muscle to increase the capacity to utilize and oxidize fats, race performance was impaired by 3±5%. In contrast, athletes consuming a HCHO diet over the same period improved performance by 4±4%. When focusing specifically on athletes who have won medals at major championships, the LCHF diet impaired performance by 6±11%, while equivalent caliber athletes in the same camps improved performance by 5±4%. Data are presented as mean ± SEM. Box and whisker plots for performance data displays median performance time, mean time (+) and 5-95% percentiles.

Figure 1



A
B
C
D
E
F
CHO Oxidation (g·min⁻¹)
Fat Oxidation (g·min⁻¹)
Time (min)
Baseline
Adaptation
HCHO
LCHF
+4%
-3%
+5%
-6%