Fueling Performance for Athletes & Individuals with Metabolic Disease



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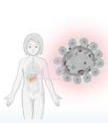
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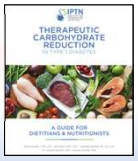
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Diabetes: Therapeutic Nutrition

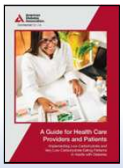












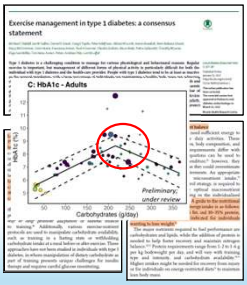
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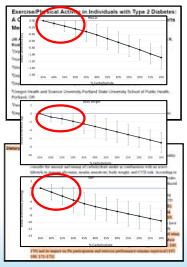
Sports Fueling: Controversy



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Diabetes: Nutrition & Exercise?

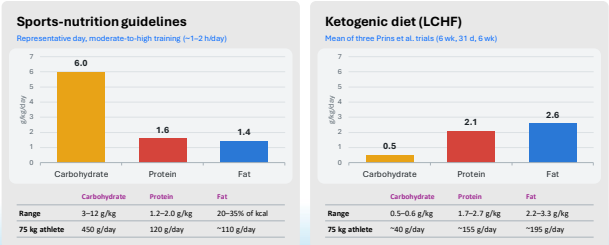




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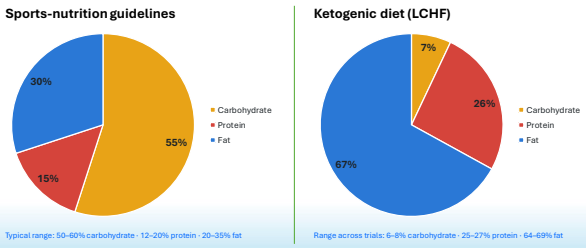
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Diet Breakdown



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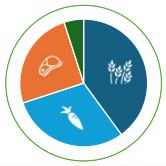
Diet Breakdown



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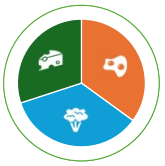
Diet Breakdown

Sports-nutrition guidelines



- **Grains & starches** ~40% of plate — Rice, pasta, bread, cereal, potatoes
- **Fruit & vegetables** ~30% of plate — Fruit, starchy and leafy vegetables
- **Lean protein** ~25% of plate — Lean meat, poultry, fish, milk
- **Added fats** ~5% of plate — Small amounts of oil, nuts

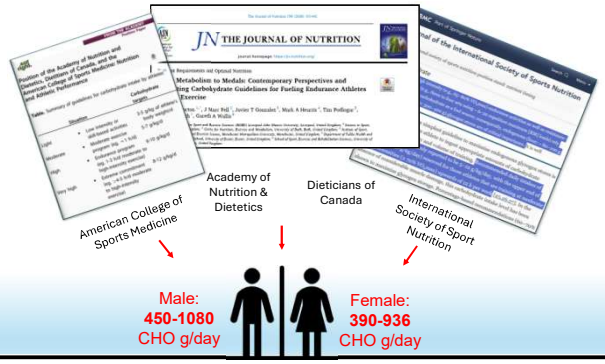
Ketogenic diet (LCHF)



- **Protein foods** ~25% of plate — Beef, poultry, fish, eggs
- **Non-starchy vegetables** ~35% of plate — Salads, leafy greens, low-starch vegetables
- **Fats & high-fat dairy** ~30% of plate — Cheese, heavy cream, oils, nuts, seeds, peanut butter

Limited: fruit and juice, bread, cereal, rice, beans, sweets, most dairy

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Century of Sport Nutrition – 1936 Berlin Games

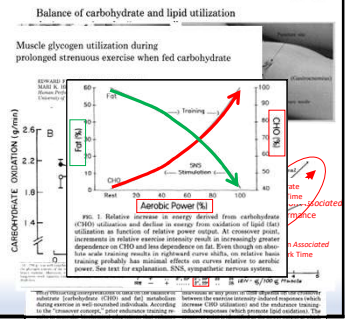


- 1936 Berlin Games: >800 g meat/day (>300g protein/day)
- Olympic Games predominantly protein-focused with higher fat content from 1896-1968 *(Pelly et al. 2011)*

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Century of Sport Nutrition – Historical Context

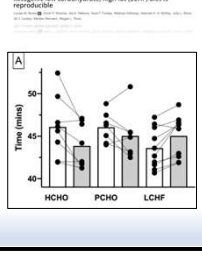
- 1920s: "*Carbohydrates improve performance*"
  - ***Carbohydrate intake before the Boston Marathon***
  - ***Improved marathon time*** (*Levin & Gordon et al. 1924-1925*).
- 1960s: "*Carbohydrate-loading strategies*"
  - Jonas Bergstrom's muscle biopsy technique.
  - **Muscle glycogen content was associated with performance** (*Bergstrom et al. 1967*).
- 1983-89: "*Intra-exercise carbohydrate fueling*"
  - Measured substrate oxidation during exercise
  - **Carbohydrate oxidation** *associated* with exercise performance (*Coyle & Coggan et al. 1983-1989*)
- 1994: "*Carbohydrates are essential for high-intensity performance*"
  - Measure FAT and CARB oxidation are different exercise intensities
  - ***"Crossover" concept* emerged: As** *exercise intensity* increased, carbohydrate use INCREASED and fat oxidation DECREASED (*Brooks & Mercier 1994*).



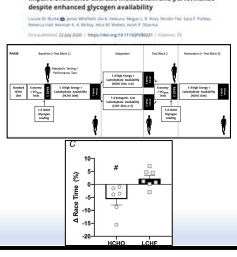
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Century of Sport Nutrition – Historical Context

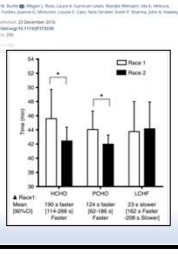
2017: 3-Week Ketogenic Diet Impaired Exercise Economy



2020: 5-6 Day Ketogenic Diet Impaired Exercise Economy & Performance (2.2%)

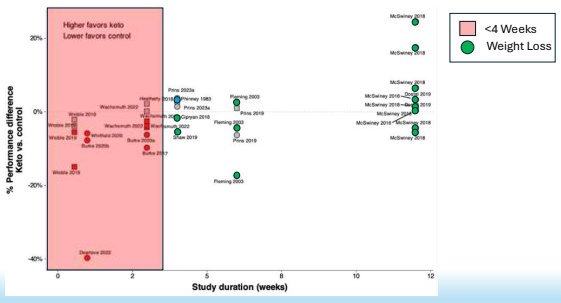


2020: 3 Week Ketogenic Diet Reduced Performance (2.3%)



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Ketogenic Diet – Performance Outcomes



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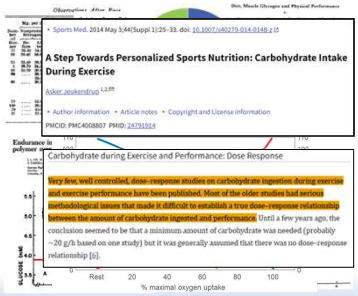
Central Tenets – High Carbohydrate Sports Nutrition

1. Lower dietary carbohydrate intake for ≤3 weeks **may lead to a marginal reduction in performance (2%)** (2017-2020)
2. "Cross-over" concept suggests that **high-intensity exercise (≥85% VO_2max)** ***requires*** **carbohydrates,** and fat oxidation cannot sustain high-intensity performance (1990s)
3. Carbohydrate intake increased carbohydrate oxidation, and **carbohydrate oxidation is associated with performance** (1980s)
4. Carbohydrate increases glycogen content, and reduced **glycogen content is associated with fatigue** (1960s)
5. Carbohydrate pre-exercise **improves performance** (1920s)

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Limitations of High-Carbohydrate Sports Nutrition Guidance

1. **Short-term adaptation:**
   - Studies showing impaired performance on low-carb diets or KD were ≤3 weeks
2. **"Cross-over" relies on assumptions:**
   - Cross-over concept was developed from *high-carbohydrate diet* and *assumes* fat oxidation cannot sustain high-intensity exercise.
3. **Association =/= *causal*:**
   - Glycogen and carbohydrate oxidation are associated with fatigue but have never been proven to be "causal."
   - ALL prior studies that show performance improvement of carbohydrate ALSO mitigated hypoglycemia.
4. **Optimal amount of carbohydrates still undetermined:**
   - Optimal carbohydrate intake recommendations (60-120g/hour) are based on models which assume the crossover concept applies to all dietary contexts and that glycogen and carbohydrate oxidation have a casual role in performance.
   - CHO dose-response studies are limited and most failed to show any clear performance benefit of more versus less CHO.

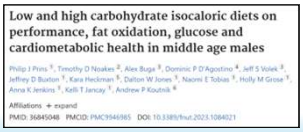


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Emergent Evidence: Diet & Performance





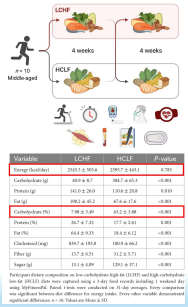




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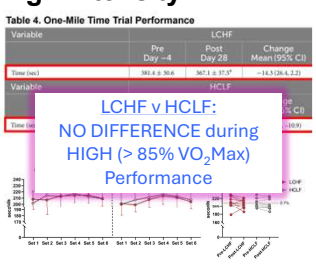
High Carb vs KD in Middle-Aged Athletes

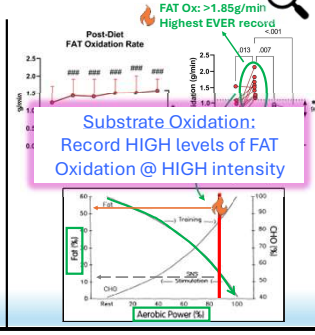
- 10 Competitive Male Runners – Middle Age
- 4-Week Isocaloric Diets:
  - High-Carbohydrate (384g/day)
  - Very-Low Carbohydrate (41g/day)
- Key Controls: Diet, Calories, Activity, Bodyweight, Diet Monitoring (Ketones & CGM)
- HIGH-Intensity Performance Testing (>85% VO2Max)
  - 1.6-Kilometer Time Trail
  - Sprint Test: 6x800m Test



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Ketogenic Diet (4w): High Intensity

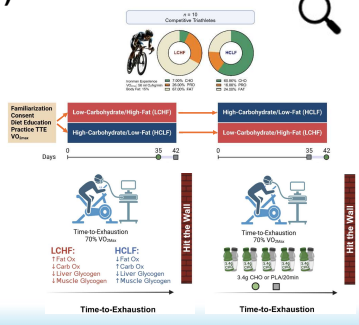




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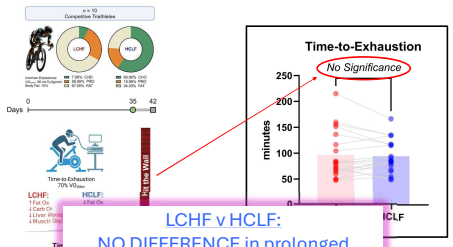
Keto-Adaptation (4-6w): Running Performance

- 10 Ironman Competitors
- 6-Week Isocaloric Diets:
  - High-Carbohydrate (380g/day)
  - Very-Low Carbohydrate (40g/day; (↓muscle glycogen)
- Key Controls: Diet, Calories, Activity, Diet Monitoring (Ketones & CGM)
- Prolonged-Strenuous Exercise Performance (HCLF v LCHF)
  - "Hitting the Wall" (70% VO2Max)
  - 15-hour post-prandial fast (↓liver glycogen)
- HLCF v LCHF + 3.4g/ hour Performance
  - Carbohydrate-Dosing: 6-12x Lower Than Current Recommendations



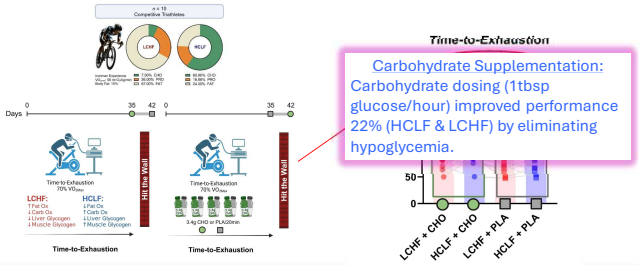
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Ketogenic Diet (4-6w): Multi-hour 70% VO2Max



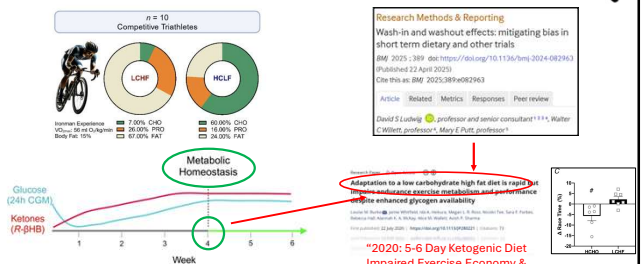
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Ketogenic Diet (4-6w): Multi-hour 70% VO2Max



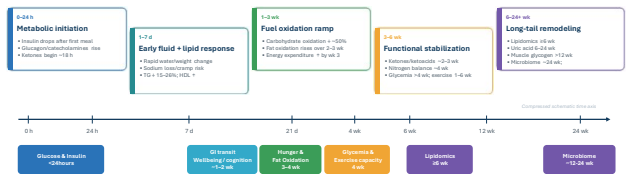
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Ketogenic: Diet Duration Impact



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Ketogenic Diet: Acute Signal =/= Full Adaptation



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"Keto-Adaptation" Timeline

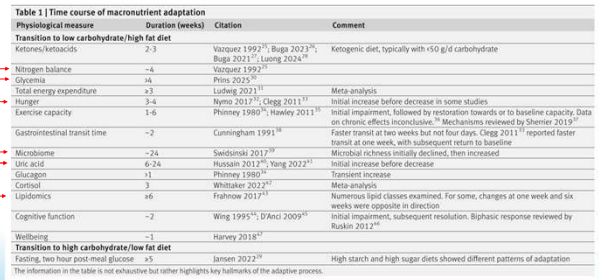


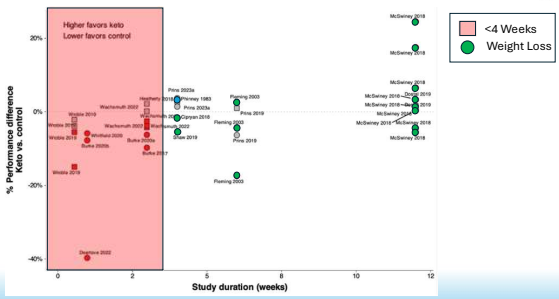
Table 1 | Time course of macronutrient adaptation

Physiological measure	Duration (weeks)	Citation	Comment
Transition to low carbohydrate/high fat diet			
Ketones/ketoacids	2-3	Vazquez 1992[25]; Buga 2023[26]; Buga 2021[27]; Luong 2024[28]	Ketogenic diet, typically with <50 g/d carbohydrate
Nitrogen balance	~4	Vazquez 1992[25]	
Glycemia	>4	Prins 2025[30]	
Total energy expenditure	≥3	Ludwig 2021[31]	Meta-analysis
Hunger	3-4	Nymo 2017[32]; Clegg 2011[33]	Initial increase before decrease in some studies
Exercise capacity	1-6	Phinney 1980[34]; Hawley 2011[35]	Initial impairment, followed by restoration towards or to baseline capacity. Data on chronic effects inconclusive.[36] Mechanisms reviewed by Shernier 2019[37]
Gastrointestinal transit time	~2	Cunningham 1991[38]	Faster transit at two weeks but not four days. Clegg 2011[33] reported faster transit at one week, with subsequent return to baseline
Microbiome	~24	Swidsinski 2017[39]	Microbial richness initially declined, then increased
Uric acid	6-24	Hussain 2012[40]; Yang 2022[41]	Initial increase before decrease
Glucagon	>1	Phinney 1980[34]	Transient increase
Cortisol	3	Whittaker 2022[42]	Meta-analysis
Lipidomics	≥6	Frahnow 2017[43]	Numerous lipid classes examined. For some, changes at one week and six weeks were opposite in direction
Cognitive function	~2	Wing 1995[44]; D'Anci 2009[45]	Initial impairment, subsequent resolution. Biphasic response reviewed by Ruskin 2017[46]
Wellbeing	~1	Harvey 2018[47]	
Transition to high carbohydrate/low fat diet			
Fasting, two hour post-meal glucose	≥5	Jansen 2022[29]	High starch and high sugar diets showed different patterns of adaptation

The information in the table is not exhaustive but rather highlights key hallmarks of the adaptive process.

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Ketogenic Diet - Timeline



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Central Tenets of High-Carbohydrate Nutrition

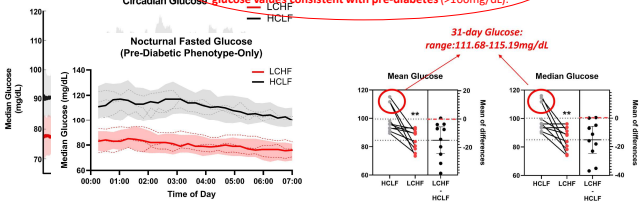
Central Tenets of High-Carbohydrate Nutrition in Sport Performance

#	Central Tenet(s)	Evidence Limitations	Evidence
1	Lower dietary carbohydrate intake for ≤3 weeks may lead to a marginal **reduction in performance.**	**Short-term adaptation:** All studies showing impaired performance on low-carb diets or KD were ≤3 weeks.	**Failed Rigorous Testing >4 Weeks** (Prins et al. 2023; Koutnik et al. 2023; Prins et al. 2024; McSwiney et al. 2017)
2	"Cross-over" concept suggests that **high-intensity exercise (≥85% VO_2max) requires carbohydrates. Fat oxidation cannot sustain high-intensity performance.**	**"Cross-over" relies on assumptions:** Concept was developed from a high-carbohydrate diet and assumes fat oxidation cannot sustain high-intensity exercise (remains untested).	**Failed Rigorous Testing** (Prins et al. 2023a & b; Koutnik et al. 2023; Prins et al. 2024)
3	Carbohydrate intake increases carbohydrate oxidation. **Carbohydrate oxidation is associated with performance.**	**Association ≠ causal:** Glycogen and carbohydrate oxidation are associated with fatigue but have never been proven to be "causal." All prior studies that show performance improvement with carbohydrate also mitigated hypoglycemia.	**Failed Rigorous Testing** (Prins et al. 2023a & b; Koutnik et al. 2023; Prins et al. 2024)
4	Carbohydrate increases glycogen content. **Reduced glycogen content is associated with fatigue & reduced performance.**		
5	**Carbohydrate pre- and during exercise improves performance.**	**Optimal amount of carbohydrates still undetermined:** Current CHO dose recommendations (60-120g/hour) are based on assumptions (i) crossover concept and a (ii) casual role of glycogen/CHO oxidation. CHO dose-response data are limited, and most studies show no clear benefit of more vs. less CHO.	**Dose Required Under Question** (Prins et al. 2024)

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Risk of Higher Carb Intake in Athletes?

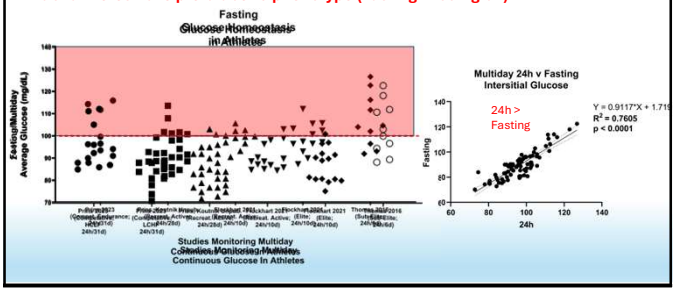
30% of middle-aged athletes (no known risk factors) on HIGH-carbohydrate diets developed interstitial **fasting** Circadian Glucose **glucose values consistent with pre-diabetes** (>100mg/dL).



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Athletes: Dysglycemia

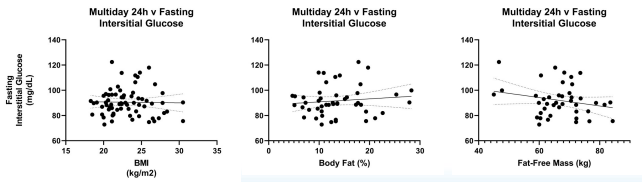
14% of athletes have pre-diabetic phenotype (Fasting >100mg/dL)



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Athletes Dysglycemia: Predictors?

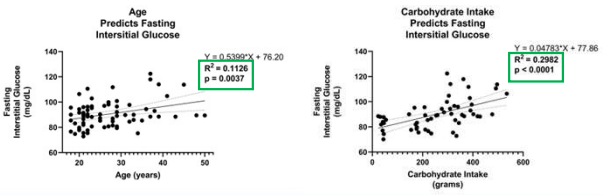
Body Composition is not associated with dysglycemia in athletes



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Athletes Dysglycemia: Predictors?

Age & carbohydrate intake are associated with dysglycemia in athletes



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Fueling for Metabolism & Performance?



endocrine reviews — ENDOCRINE SOCIETY

Carbohydrate Ingestion on Exercise Metabolism and Physical Performance

Timothy D. Noakes,[1] Philip J. Prins,[2] Alex Buga,[3] Dominic P. D'Agostino,[4,5] Jeff S. Volek,[3] and Andrew P. Koutnik[3,6]

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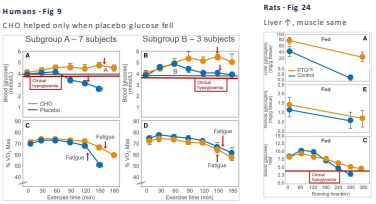
Correspondence: Andrew P. Koutnik, PhD, Institute for Sports Science and Medicine, Department of Health, Nutrition, and Food Sciences, Anne's College of Education, Health, and Human Sciences, Florida State University, 1104 Spirit Way, Ste 140, Tallahassee, FL 32506, USA. Email: andrewkoutnik@gmail.com.

100 Years of Evidence. >600 Studies. >160 Carbohydrate Sports Performance Trials

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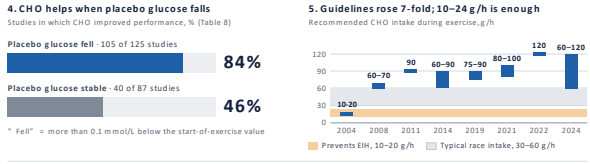
Fatigue Tracks Falling Blood Glucose Not Muscle Glycogen

1. Association, not causation
   - Muscle glycogen: ATP does not fall at exhaustion, and muscle rigor NEVER occurs.
   - Fatigue is primarily brain-regulated brake against hypoglycemia
2. Small glucose pool (hepatic glycogen & circulating glucose) decides
   - Blood (~5g glucose) and liver glycogen, not muscle glycogen (500-800g), set when exercise stops.
3. Causal evidence? Small glucose pool
   - Preclinical causal investigation demonstrated liver glycogen held glucose steady and extended performance. However, similar causal investigation into muscle glycogen DID NOT regulate performance.
   - Blocking gluconeogenesis cut performance 23%



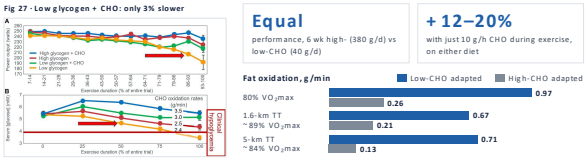
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Fat-adapted athletes perform as well, so guidelines should individualize



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Fat-adapted athletes perform as well, so guidelines should individualize



Equal
performance, 6 wk high- (380 g/d) vs low-CHO (40 g/d)

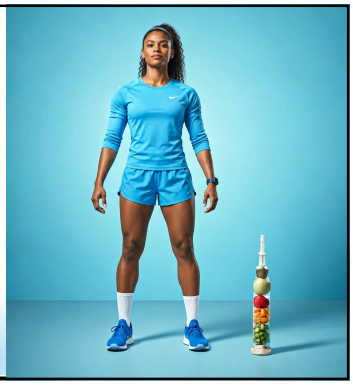
+ 12–20%
with just 10 g/h CHO during exercise, on either diet

Implication. Replace blanket high-carbohydrate targets with individualized plans that protect blood glucose at the minimum effective dose, most relevant beyond 2–3 h and in athletes with limited hepatic glucose output.

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Conclusions & Key Take Homes

1. Diet remains controversy remains between various diets in athletes with and without metabolic disease.
2. Ketogenic diets reduce carbohydrate intake (<50 g/day; <10% EI), resulting in both acute (≤24 hours) and chronic metabolic adaptation (6 months).
3. Emergent evidence **>4 weeks in duration, controlling key confounders (calories, activity, body mass)**:
   - NO performance decrements of very-low carbohydrate or ketogenic diets if athletes adapted ≥4 Weeks.
   - Short-term adaptation may lead to transient performance declines.
   - Performance appears to be regulated by multiple factors, with maintaining brain energy metabolism being the most consistently reported physiological impact related to performance improvements
4. Many athletes may need to consider diet choice for reasons beyond performance (health). Individualization is important. Health is most important.



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