

Introduction to Exercise Physiology and Metabolism

EID 424
Bioengineering Applications in Sports Medicine
Nov 1, 2021
Prof Kremenec

1

A cursory Overview of...

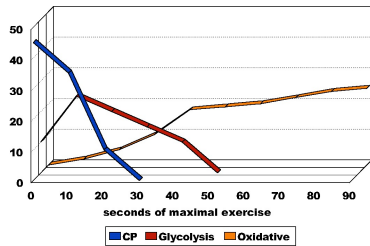
- + Exercise physiology
- + Metabolism
- + Nutrition
- + Ergogenic aids
- + Weight loss

2

Pathways for Energy Generation

3

Fuel Sources During Exhausting Exercise



4

Creatine Phosphate

- + $\text{ADP} + \text{CP} \rightarrow \text{ATP} + \text{Creatine}$
- + Anaerobic
- + Always first mode of ATP generation
- + Greatest rate of ATP production, short duration
 - + Lasts 4-11 secs
- + Re-synthesis is oxygen-dependent
 - + 90% in 10 minutes
 - + Takes up to one hour for total repletion

5

Anaerobic Glycolysis

- + Uses glucose and glycogen stored in muscle
- + Provides ATP for up to 40 secs of work
 - + 40-50% peak yield of CP
- + Produces lactate
 - + Must be metabolized aerobically
 - + Lactic acid buffered by bicarbonate, which produces CO_2

6

Oxidative Metabolism

- + Glucose, fats, protein
 - + Fat, protein must first be converted to glucose!
- + Theoretically, endless energy supply
- + Slowest rate of ATP production
 - + 75% of that generated by glycolysis
 - + Most efficient ATP production

7

Aerobic vs Glycolytic ATP Generation

- + Glycolysis
 - + One glucose generates 2 ATP
 - + + lactic acid
- + Aerobic
 - + One glucose generates 38 ATP

8

Energy Sources for Exercise

- | | |
|------------------|-----------------|
| + Anaerobic | + Aerobic |
| + High-intensity | + Long-duration |
| + Short-duration | + Low-intensity |

Type II motor units vs Type I motor units

9

Energy Sources for Exercise

- + “Hitting the wall”
 - + Depletion of muscle glycogen
- + Eating some carbohydrate *immediately* post-exercise is a good idea
 - + Muscle trying to replenish glycogen stores
 - + Quickly absorbed
 - + Absorption *not* mediated by insulin

10

Recovery

- + Post-exercise consumption of energy enables better recovery
 - + Immediate repletion of glycogen stores
 - + Better able to compete/work out at high intensity the next day
- + Carb important
 - + Quickly absorbed
- + Some protein also needed
 - + Rebuild muscle
- + Chocolate milk

11

Fatigue Issues

- | | |
|--|--|
| + Central fatigue <ul style="list-style-type: none">+ Failure of nervous system to drive muscles | + Peripheral fatigue <ul style="list-style-type: none">+ Decrease in force generation is failure at muscular level |
|--|--|

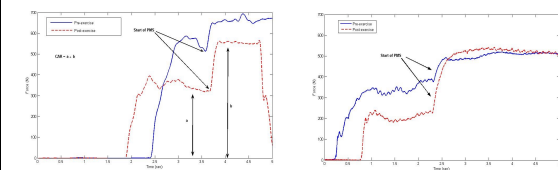
12

Fatigue Issues

- + Determination of fatigue: the interpolated twitch technique [ITT, Merton, 1954]
 - + Have subject perform maximal contraction
 - + Superimpose electrical stimulus
 - + If additional force generated with stim, fatigue is central

13

Central vs Peripheral Fatigue



14

Fatigue Issues

- + Primary energy source for muscles is glycogen in muscle
- + Brain requires glycogen from blood
 - + Drop in blood sugar is issue for brain, not muscle
 - + Blood sugar typically maintained during exercise
 - + Very recent evidence suggests brain has some stores of glycogen
 - + Stay tuned

15

New Thinking on Fatigue

- + Central nervous system can sense drop in muscle glycogen levels
 - + “Glycostat” [Noakes, St Clair Gibson]
- + Drop in muscle glycogen *may* decrease central drive to muscle
- + Impending availability of glycogen may increase central drive
 - + Mouth rinse studies

16

Measuring Fitness

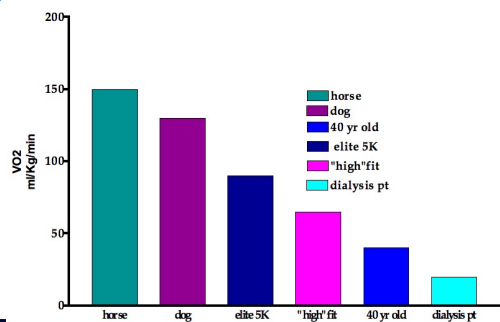
17

VO_{2max}

- + Maximum rate of oxygen consumed
 - + Higher VO_{2max}, more fit
- + Measured in L/min
 - + Normalize to ml/kg/min
 - + Over 50 ml/kg/min for trained/fit subjects
- + Different depending on method used to test
 - + VO_{2max} treadmill > VO_{2max} bike
 - + Running activates more muscles than bike (mostly quads)

18

Representative $\text{VO}_{2\text{max}}$ Values



19

Determinants of Oxygen Consumption

- + $\text{VO}_2 = \text{C.O.} \times (\text{A-V } \text{O}_2 \text{ diff})$
- + Cardiac output
 - + (Stroke volume) \times (heart rate)
 - + Stroke vol: amount of blood pumped with each beat
- + Arterial-venous difference
 - + Oxygen carrying capacity
 - + Oxygen extraction

20

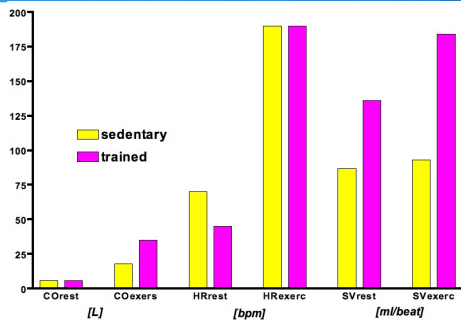
Measurement of Oxygen Consumption

- + Metabolic cart
 - + Measure exhaled gases, compare to room air
 - + Partial pressure of O_2 , CO_2
- + Also used to determine resting metabolic rate
 - + Number of calories needed to exist without moving



21

Cardiovascular Adaptations to Training



22

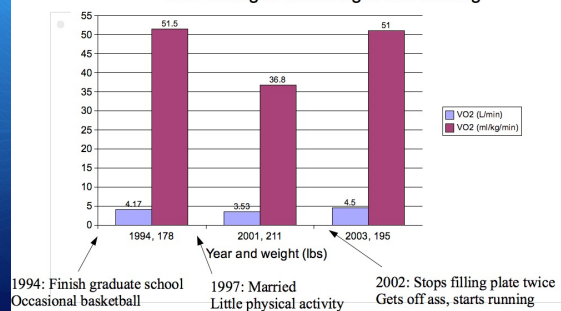
Maximal Heart Rate Rule-o-Thumb

- + Max heart rate is $220 - \text{age}$
- + This is a *very rough estimate*

23

Effect of Weight and Training on an Engineering Graduate

VO2 changes with weight and training



24

Pro Team-Sport Players

- + $\text{VO}_{2\text{max}}$ usually in “high fit” range
- + Soccer [55-65 mls/kg/min] > hockey [50-60] > basketball > football > baseball
- + Anaerobic capacity > than normal
 - + Most of these require short bursts of high-intensity work
- + Aerobic base thought to help recover from anaerobic exercise

25

Anaerobic Threshold

- + Point at which venous lactate increases
 - + Also called lactate threshold, ventilatory threshold, first threshold
- + Ventilation increases non-linearly
 - + Estimate using break point of ventilation/ VO_2 curve
- + Determined by recruitment of fast-twitch fibers
- + Work starts to feel difficult
- + Typically, 65%-75% $\text{VO}_{2\text{max}}$ in trained individuals

26

Respiratory Compensation Threshold

- + RCT, second threshold
- + Ventilation increases non-linearly again
 - + Another break point of ventilation/ VO_2 curve
- + Further increase in lactate production
 - + Near maximal exercise
 - + Rate of lactate production > ability to buffer
 - + Uncompensated metabolic acidosis
 - + Ventilation driven by need to blow off excess CO_2
- + Very hard effort to maintain

27

Respiratory Exchange Ratio

- + RER
- + Ratio of CO_2 expired to O_2 consumed
- + < 0.7 : using almost 100% fat
- + > 1.0 : using almost 100% carbohydrate
 - + Work starts to feel uncomfortable
- + Max test: want to see RER > 1.2

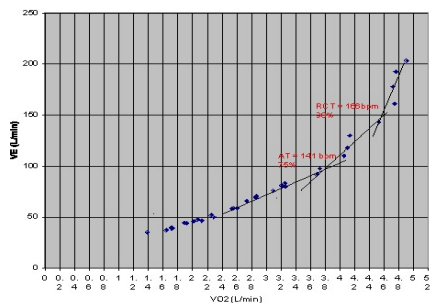
28

Training Intensity

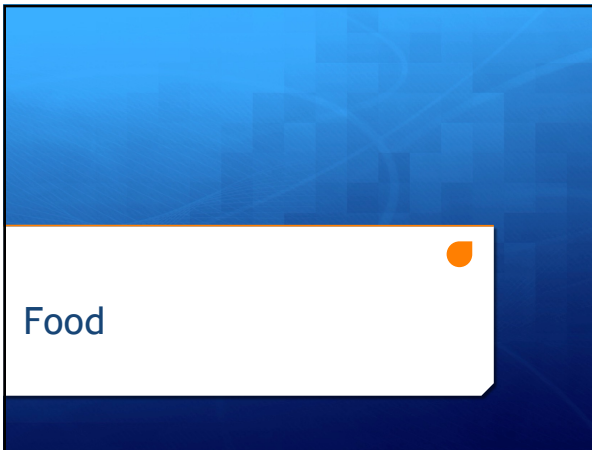
- + Measure AT, RCT using metabolic testing system
- + Typical training (i.e., long runs, rides) done around AT
- + Sprint, interval training done near RCT
- + Use heart rate for each threshold as a guide
 - + Easy to run with heart rate monitor, not so easy with large metabolic cart

29

Determination of AT and RCT



30



31

Nutrition

- + Your food is composed of:
 - + Carbohydrate
 - + Sugars
 - + Glucose/glycogen
 - + Starches
 - + 4 C/gm
 - + Protein
 - + Meat
 - + Eggs [white]
 - + 4 C/gm
 - + Fat
 - + Meat
 - + Nuts
 - + Oils
 - + 9 C/gm

32

A Note About Calories

- + Measure of heat
- + Food Calories
 - + Upper-case "C"
- + Chemistry
 - + kcals

33

Fat

- + Fat is body's long-term storage
- + Any excess calories consumed are converted to fat for storage for a rainy day
- + 1 lb fat = 3500 C
- + 100 C/day in excess of daily requirements:
 - + = 700 C/wk
 - + = 1 lb/5 wks
 - + = 10 lbs/yr
- + Drink one less glass of soda/day, lose 10 lbs in a year
 - + And don't replace with something else

34

Weight Loss

- + Burn more calories than consumed
 - + Eat less
 - + 1 serving of meat = 3 oz = size of deck of cards
 - + Exercise more
 - + Hard to do during competitive season while maintaining performance
- + We believe in conservation of energy:
 - + Too many calories make one fat
 - + Carbs do not make one fat
 - + Excessive carbs make one fat
 - + Excessive *anything* makes one fat
 - + *The Hacker's Diet*
 - + John Walker
 - + Founder of AutoDesk, co-author of AutoCAD
 - + <http://www.fourmilab.ch/hackdiet/>

35

The Problem With Weight Loss

- + Essentially, starving yourself
- + This is unpleasant
- + This is easily-remedied for little money
 - + Snickers ® bar = ~ \$1
- + No one estimates their intake well without writing everything down

36

Weight Loss

- + Fat and protein are necessary
 - + For physiology/metabolism
 - + Harder to digest
 - + Remain in stomach longer
 - + Make you feel "full"
- + Keep blood sugar more level
 - + Low blood sugar makes you feel hungry
 - + Eating only simple sugars causes blood sugar to spike and then plummet
 - + Pancreas releases too much insulin
 - + Reactive (rebound) hypoglycemia
 - + Hungry again

37

Weight Loss

- + Exercise causes body to burn more calories
 - + Depressingly few
 - + 450 cals for 170 lb man running 30 mins at 8 min/mi
 - + One Snickers® = 280 cals
 - + Amount depends on
 - + Weight of person
 - + Duration/intensity of exercise
 - + Running one mile burns same number of calories as walking one mile (more or less)
- + Exercise does have many other health benefits

38

Sex Differences

- + Exercise tends not to aid weight loss in women
 - + Increase caloric intake to offset exercise
 - + Drive to reproduce
 - + Bodyfat too low → cessation of menstruation
 - + ~15%

39

Health Benefits of Exercise

- + Weight maintenance
- + Stay healthier until death
- + Evidence for prescribing exercise as therapy in chronic disease
 - + Pedersen, Saltin
 - + "Exercise as medicine"
 - + Exercise more effective than medication in controlling blood sugar in diabetes
 - + 61 pages of good stuff
- + Swedish golf paper
 - + Farahmand et al, 2008
 - + Golf players 40% ↓ mortality (~5 yrs ↑ life expectancy)
 - + In Sweden (population already healthy)
- + "Exercise is medicine"TM
- + ...

40

Interesting Aside...

- + Humans are evolved to run?
 - + We are lousy sprinters
 - + We are excellent distance runners
 - + And we can dissipate heat by sweating rather than panting
- + *Persistence hunting* may have been the key to allow our brains to develop
 - + Let's us eat meat
- + Daniel Lieberman (Harvard)
 - + Check out NOVA archives



41

Wanna Live Longer?

- + Caloric restriction (~25%)
- + Extends lifespan in *every* life form thus far studied
 - + Yeast
 - + Monkeys



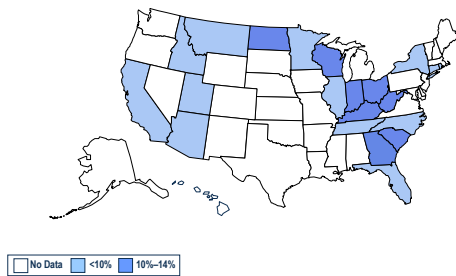
42

Scary Weight Loss Aside

- + Obesity trends in US in past ~35 yrs [CDC:
<http://www.cdc.gov/nccdphp/dnpa/obesity/trend/maps/>]
 - + Based on body mass index
 - + 30 lbs overweight for 5' 4"
 - + This discussion will stop at 2010 because of a change in the inclusion criteria/scaling
- + Body mass index
 - + BMI
 - + $Wt/(ht^2)$ [kg/m²]
 - + [lbs/in²] * 703
 - + < 18.5: underweight
 - + 18.6 – 24.9: normal
 - + 25 – 29.9: overweight
 - + > 30: obese
 - + Not perfect
 - + Very muscular will have high BMI

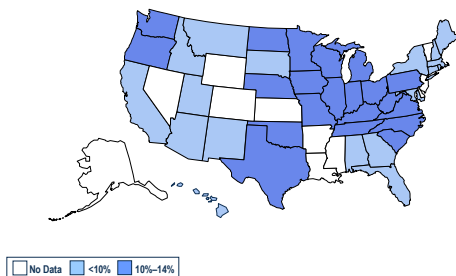
43

Obesity Trends in Adults, 1985



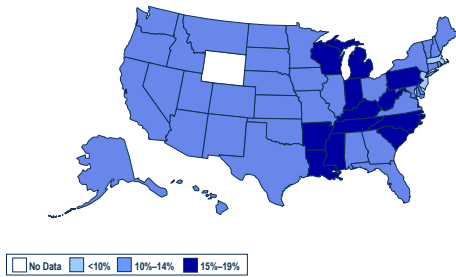
44

Obesity Trends in Adults, 1989



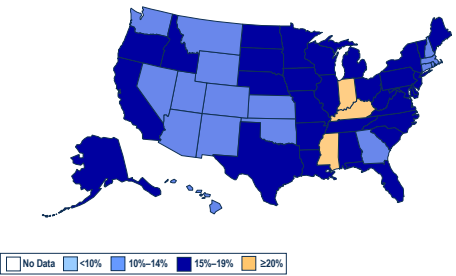
45

Obesity Trends in Adults, 1993



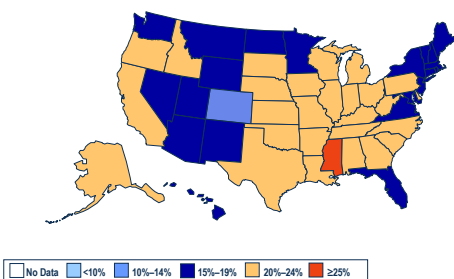
46

Obesity Trends in Adults, 1997



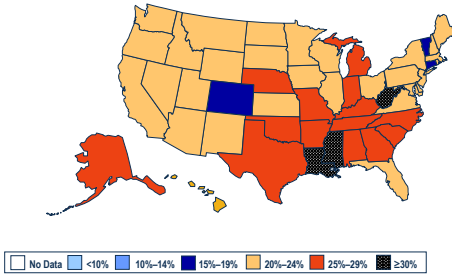
47

Obesity Trends in Adults, 2001



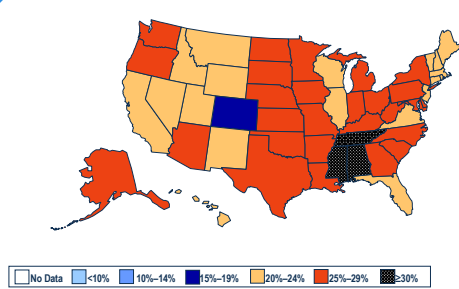
48

Obesity Trends in Adults, 2005



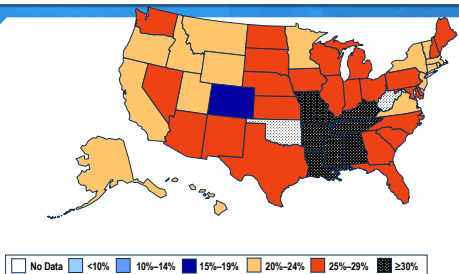
49

Obesity Trends in Adults, 2007



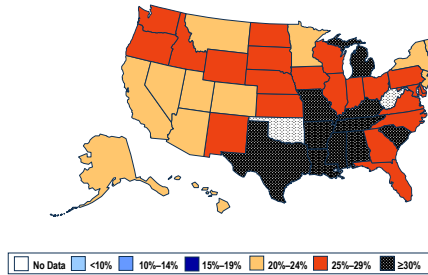
50

Obesity Trends in Adults, 2009



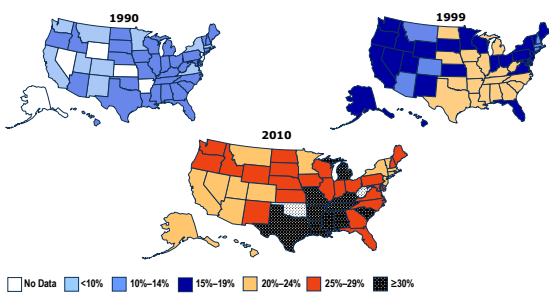
51

Obesity Trends in Adults, 2010



52

Trouble



53

Consequences

- + Huge burden to health care system
- + Metabolic syndrome
 - + Syndrome X
 - + Overweight
 - + High body fat
 - + High cholesterol
 - + Hypertension
- + Technological interventions for exercise/weight loss:
 - + *Dance Dance Revolution* had a moment in the sun
 - + Wii
 - + Xbox Kinect
 - + Smart watches/devices

54

Diabetes

- + Type I
 - + Formerly childhood diabetes
 - + Autoimmune
 - + Pancreas unable to produce enough insulin
- + Type II
 - + Formerly adult-onset
 - + Body resistant to insulin, reduced insulin sensitivity
 - + **Obesity**
 - + Seen now in children
- + Exercise improves insulin sensitivity

55

Diabetes

- + Systemic effects
 - + Vulnerable to infection
 - + Neuropathies (decreased sensation)
 - + Amputation
 - + Blindness
 - + Kidney/liver failure
 - + Uncontrolled blood sugar
 - + Diabetic ketoacidosis (DKA)

56

Wise Words

- + Michael Pollan
 - + *Omnivore's Dilemma*
 - + *In Defense of Food: An Eater's Manifesto*
- + "Eat food. Not too much. Mostly plants."
- + "Real" food = anything your grandmother would identify as food

57

Performance [Ergogenic] Aids

58

Sports Drinks

- + Water combined with
 - + Carbohydrate
 - + Salt (not just NaCl)
- + Replace some carbohydrate and electrolyte while exercising
 - + Also, keeps you feeling thirsty, encourage more drinking

59

Sports Drinks

- + Must be high enough concentration to be effective, low enough to be easily-absorbed
 - + Food must be iso-osmolar to leave stomach, enter gut for absorption
 - + ~ 6% carb
 - + < 6% carb probably not useful
 - + > 8% can cause gastrointestinal discomfort
 - + More can be tolerated in activities with less jostling (i.e., cycling)
- + Water fine for low-intensity, short duration
 - + < 70% $\text{VO}_{2\text{max}}$ < 1 hr

60

Sports Drinks

- + Diet sports drinks
- + This makes no sense in the context of a *sports* drink to enhance performance
- + This is a replacement for soda/iced tea/etc.

61

More New Thinking on Fatigue

- + Consuming carb extends performance
- + Washing carb beverage in mouth extends performance [Carter et al., *Med Sci Sports Exerc*, 2004]
 - + Placebo (sweetened) drink does not
 - + Some feedback from mouth to brain, not just based on taste
 - + Possibly works better than actually drinking it? [Pottier et al., *Scand J Med Sci Sport*, 2010]
 - + Does not work indefinitely

62

Hydration Issues

- + Dehydration
 - + Increased heart rate
 - + Headache
 - + Dizziness (orthostatic)
 - + Decreased skin turgor
 - + Thirsty
 - + Increased temperature
 - + Increased ratings of perceived exertion
 - + Decreased performance (esp. aerobic)
 - + 2% weight loss → 10% decrease in VO₂max
 - + Not the same as heat stroke (high body temp), but often concomitant

63

Dehydration

- + Easily remedied
 - + Raise feet
 - + Helps with getting fluid out of extremities, back to core
 - + Raises blood pressure
 - + Have them drink
 - + IV if unconscious

64

Heatstroke

- + Very serious
 - + Don't want brain to boil
- + Ice bath
- + Look for confusion, mental status changes
- + Any increase in temperature greatly impairs performance

65

Hydration Issues

- + Yes, you can drink too much water
- + Hyponatremia
 - + Low plasma sodium
 - + Water shifts to intracellular fluid
 - + Leads eventually to cerebral swelling, seizures, rhabdomyolysis, death
 - + Drinking too much water over a short period of time
 - + High sweat rates
 - + Stereotype: slow runner in marathon on hot day

66

Hyponatremia

- + Long-duration exercise
 - + Marathon (or ultramarathon)
- + Recreational drug use
 - + MDMA
- + Rare psychological issue: psychogenic polydipsia
- + Look for
 - + Mental status change, confusion
 - + Nausea, vomiting
 - + Swollen extremities (tight watch, rings)

67

Cramping

- + Not caused by dehydration
- + Likely caused by fatigue
 - + Role of electrolytes?
 - + First adaptation to exercise in heat is sweat becomes more dilute
- + Look for "salty sweaters"
 - + Football player with white caked on uniform
 - + Salt packets
 - + Pickle juice
 - + Salt or vinegar?
 - + Central effect?

68

DSHEA

- + Dietary Supplement Health and Education Act of 1994
 - + Allowed for drug advertising to the public
- + Defined dietary supplements as a separate category
 - + Unregulated by FDA
 - + No approval, clinical trials
 - + Must be proved unsafe to be removed from market

69

DSHEA

- + Dietary supplement
 - + Vitamin, mineral, herb, amino acid, extract, metabolite, concentrate
 - + Intended for ingestion in pill, capsule, tablet or liquid form
 - + Not represented as food or sole item in a meal
 - + Must be labelled "dietary supplement"
 - + Cannot be called a "drug"
 - + Drug: "intended to diagnose, cure, mitigate, treat or prevent disease"
 - + Completely unregulated

70

Ergogenic Aids

- + Any method of enhancing energy production and utilization for enhancing exercise performance
 - + Mechanical
 - + Lightweight racing shoes
 - + Psychological
 - + Hypnosis
 - + Physiologic
 - + Blood doping
 - + Nutritional
 - + Vitamins
 - + Pharmacologic
 - + Anabolic steroids

71

Ergogenic Aids

- + Athletes are crazy
- + Poll of 1996 US Olympic athletes
 - + Take a substance that is not detectable, guaranteed to win
 - + 98% would
 - + Take a substance that is not detectable, guaranteed to be a winner for 5 years, *but then you will die*
 - + 50% would

72

Ergogenic Aids History

- + Greeks ate mushrooms during early Olympics
- + Aztec athletes ate human heart
- + Late 1800's European cyclists ate ether-soaked sugar tablets
- + Turn of the century (early 1900's) marathoners drank brandy and strychnine

73

Carb Loading

- + Muscles directly use carbohydrate as substrate for energy generation
 - + Primary fuel for high-intensity exercise
- + More glycogen stored in muscle should improve/extend performance
 - + Little evidence
 - + Most studies had no control group
 - + May help for long duration (>90 min) events that lead to near exhaustion

74

Carb Loading

- + **NOT** a meal of pasta the night before the event
- + 70% carb diet (4 g per pound) for a week prior
 - + 600 g for 150 lb man
 - + 2 loaves of bread or,
 - + 3 cups sugar or,
 - + 15 potatoes or,
 - + 12 cups rice
- + Recent work does show shorter duration can be effective

75

Caffeine

- + May allow athlete to train longer/harder
 - + Decreases glycogen use during first 15 mins of exercise [Spriet, 1992]
- + May increase speed/power during competition
- + 2.3 mg/lb body weight
 - + 2-3 cups of coffee
- + Monitored by IOC, NCAA
 - + > 5 mg/kg illegal in NCAA
- + Risk of dehydration, hypertension, arrhythmia

76

Ephedra

- + Banned 2004 by FDA
- + Chinese herb (*ma huang*)
- + Natural source of ephedrine
 - + The stuff in Sudafed that gets you wired
 - + Stimulant
- + Weight loss
- + Energy enhancement

77

Ephedrine and Caffeine [stimulants]

- + Increase heart rate
- + Increase time to fatigue
- + Decrease ratings of perceived exertion
- + Increase sweat rate
- + Can lead to hypertension and arrhythmias at high doses

78

Anabolic Steroids

- + Not corticosteroids
 - + Used to treat inflammation, asthma
- + Synthetic version of testosterone
- + Increase protein synthesis
- + Increase intensity of workout
 - + Still have to do the workout to achieve a benefit

79

Anabolic Steroids Adverse Effects

- | | |
|-------------------------|-------------------------------------|
| + Men | + Aggressive behavior (“roid rage”) |
| + Acne | |
| + Gynecomastia | + Weight gain |
| + Testicular atrophy | |
| + Women | + Tendon injuries |
| + Enlarged clitoris | |
| + Deepening of voice | + Liver toxicity |
| + Breast atrophy | |
| + Hirsutism | + No prospective studies |
| + Male pattern baldness | |

80

Erythropoietin

- + “Epo”
- + Glycoprotein that stimulates red blood cell production
 - + Used in patients undergoing chemotherapy
- + Replaced blood doping
- + Increase
 - + VO_{2max}
 - + Time to exhaustion
- + Hypertension
- + Hyperviscosity of blood
 - + Clots

81

Other Interesting Things

- + Sodium bicarbonate
 - + Yes, baking soda
- + Live high, train low
- + Creatine
- + Human growth hormone [hgh]
