Metabolite Extraction for Metabolomic Studies

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Resources

- Metabolomics Workbench
  - www.metabolomicsworkbench.org
  - Large resource of experimental protocols, datasets, and other resources
- XCMS Institute
  - https://xcmsonline.scripps.edu/institute
  - Great tutorials on chromatography, platforms, databases
- Twitter
  - #metabolomics

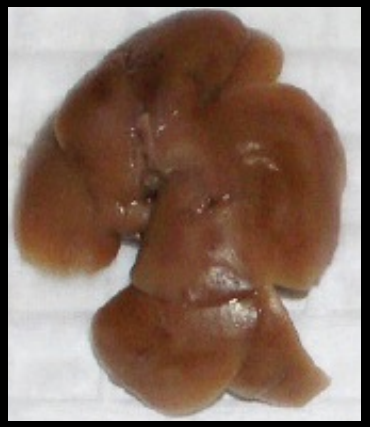
Objectives

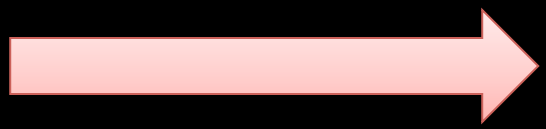
At the conclusion of this lesson, students will be able to:

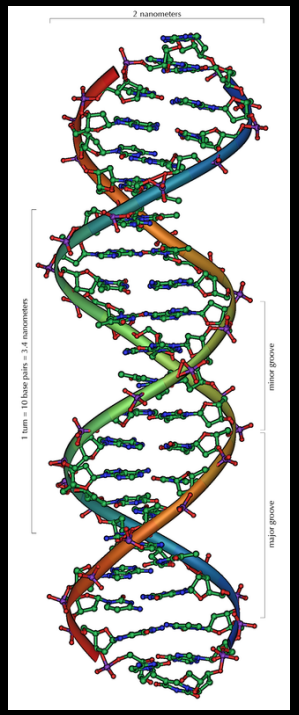
- Define factors that influence metabolite extraction and describe their impact on metabolomic studies
- Explain the value of chromatography for improved metabolite identification and quantitation

Extraction of Metabolites

Nucleic Acid Extraction



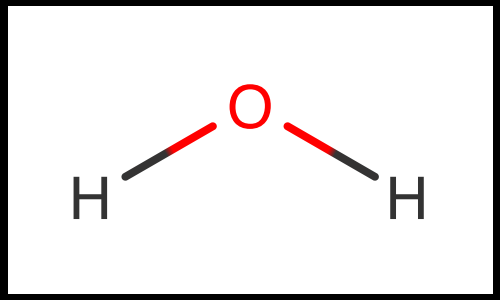


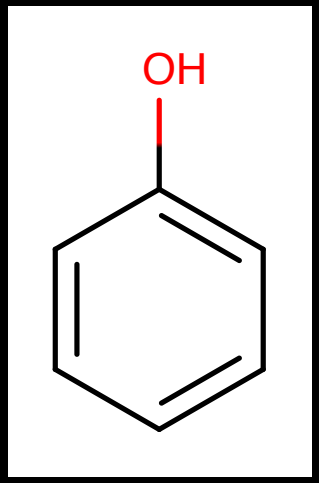


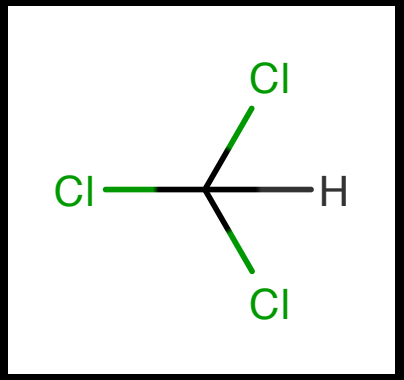
What do we know about our target analyte?

- Negatively charged phosphate backbone (polar)
- Need to remove proteins, lipids, etc

About Solvents







WATER

PHENOL

CHLOROFORM

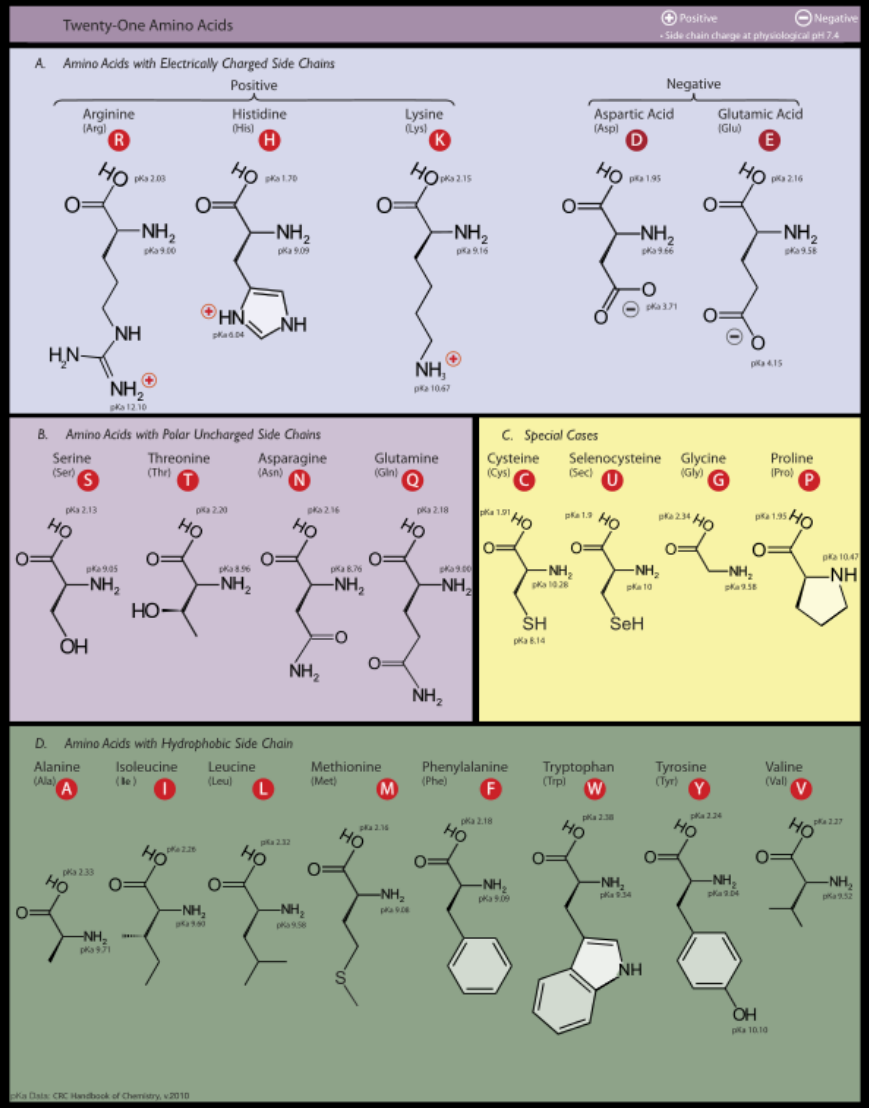
1.00 g/cm^3

1.07 g/cm^3

1.49 g/cm^3

POLARITY

Protein Chemistry

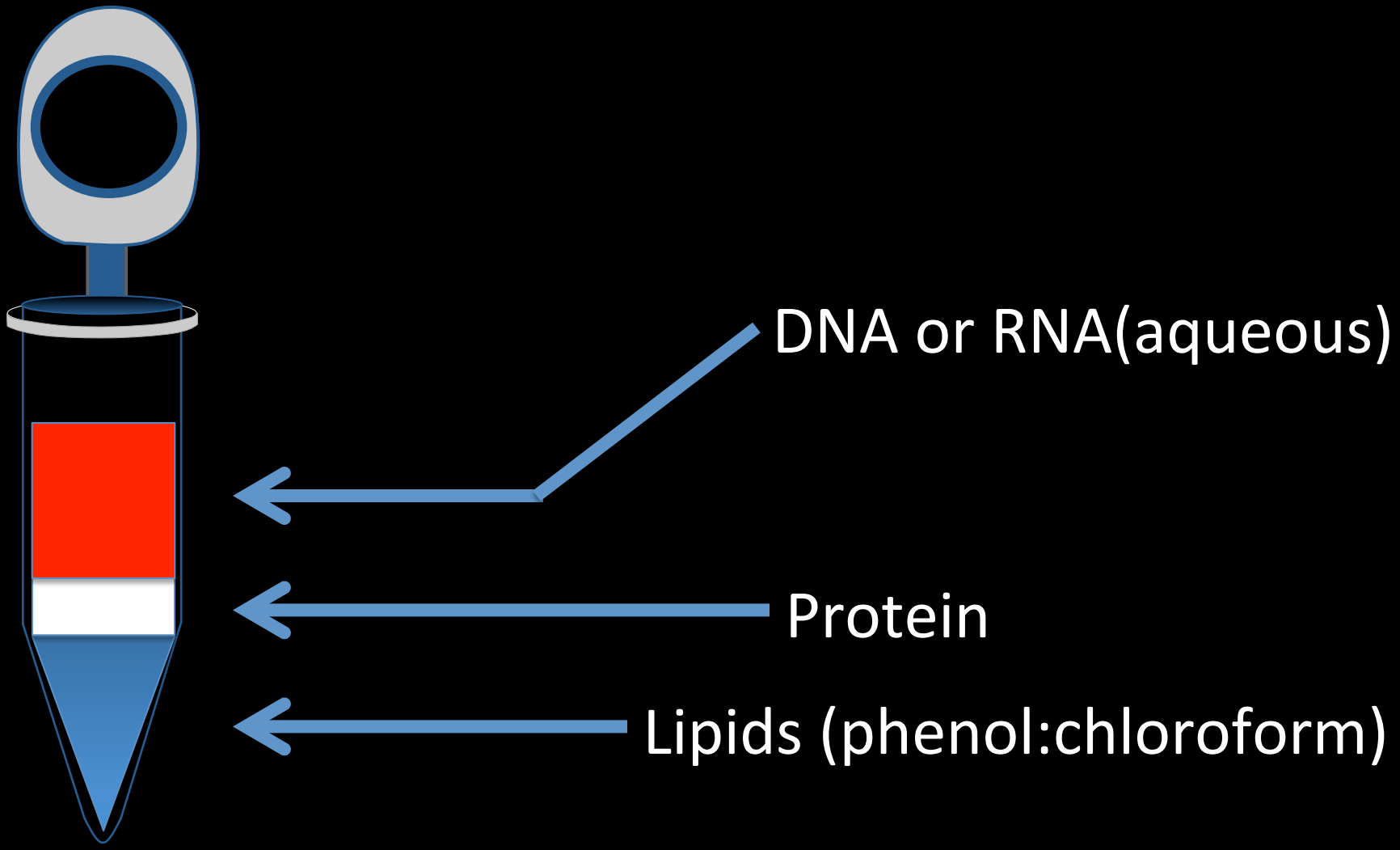


Denature proteins

- Hydrophobic amino acids face phenol:chloroform
- Phe, Tyr, Leu

https://en.wikipedia.org/wiki/Proteinogenic_amino_acid

Liquid Liquid Extraction



DNA Extraction Protocol

- Disrupt tissue in phenol:chloroform

**chloroform prevents small amounts of water in phenol from dissolving mRNA
**adjust pH to favor DNA (basic) or RNA (acidic) isolation

- Centrifuge to separate layers
- Dehydrate with alcohol

What could go wrong?

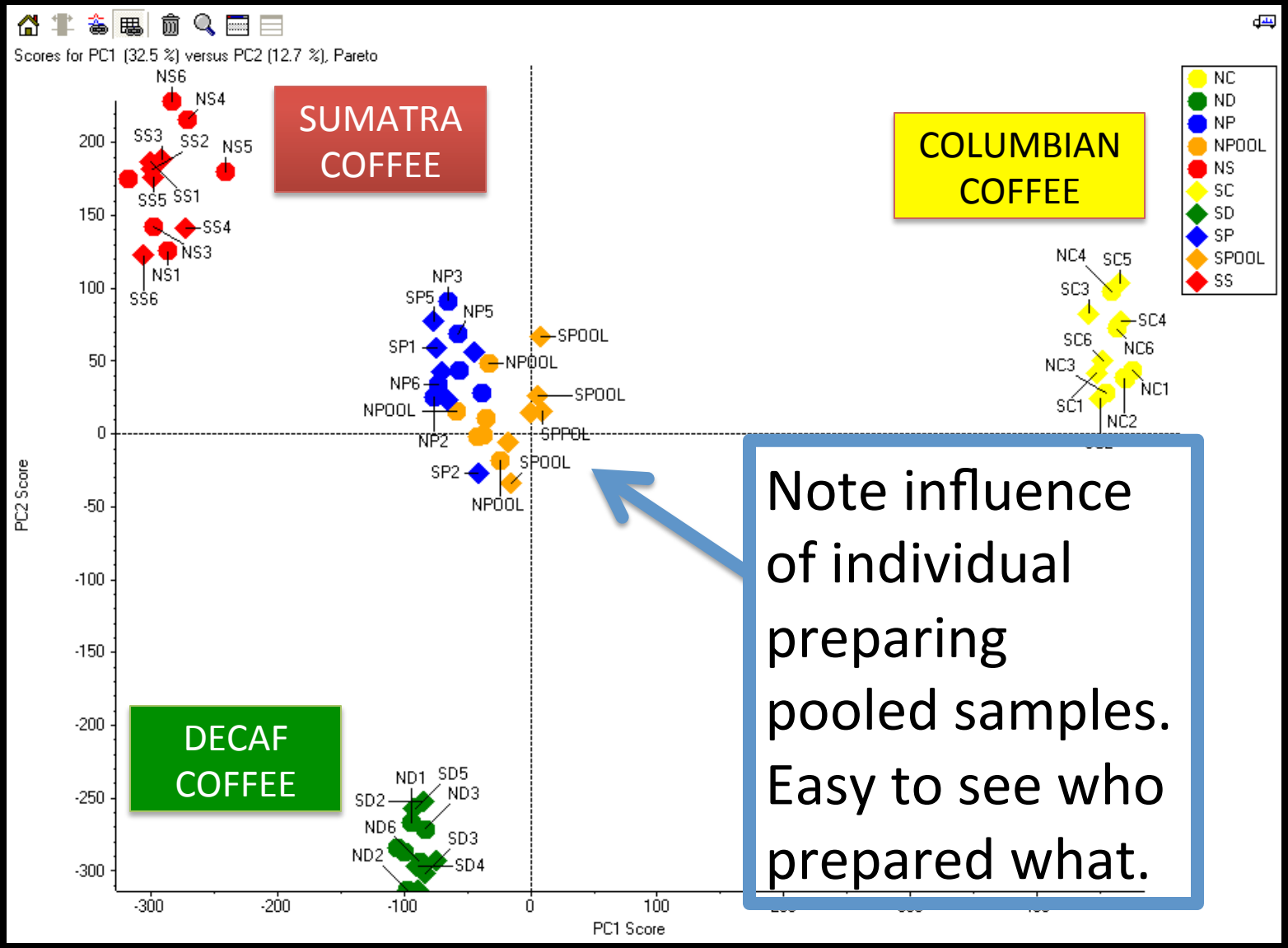
- Solvents not appropriate or prepared incorrectly
  - pH incorrect
  - Ratios incorrect
- Contamination of solvents or buffers
- What else can you think of?

Standard Operating Procedures

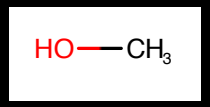
- Saves time and prevents mistakes
- Consistent results

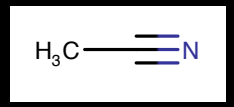
- Checking in samples (sample lists, location)
- Labeling and storing samples (aliquot)
- Metabolite extraction (targeted or global)
- Acquiring data on various platforms (MS, NMR)

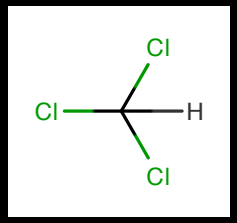
Even with SOPs…

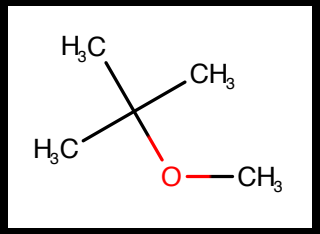


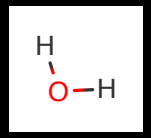
Common Solvents for Metabolomics

- Methanol 

- Acetonitrile 

- Chloroform 

- Methyl tert-butyl ether (MTBE) 

- Water 

List is not inclusive

Methanol

- Relatively inexpensive compared to acetonitrile
- Not regulated like ethanol
- Easy to evaporate

- Extracts polar and (some) non-polar molecules – why?

Acetonitrile

- Advantages mostly for chromatography
  - Reduced absorbance for UV based methods
  - Reduced pressure compared to methanol
  - Greater elution strength (generally)
  - HILIC applications

- Expensive
  - Isolated as a byproduct not produced directly
  - Shortages can influence price and availability

Chloroform vs MTBE

- Chloroform densitiy – 1.49 g/cm^3
- MTBE density – 0.740 g/cm^3

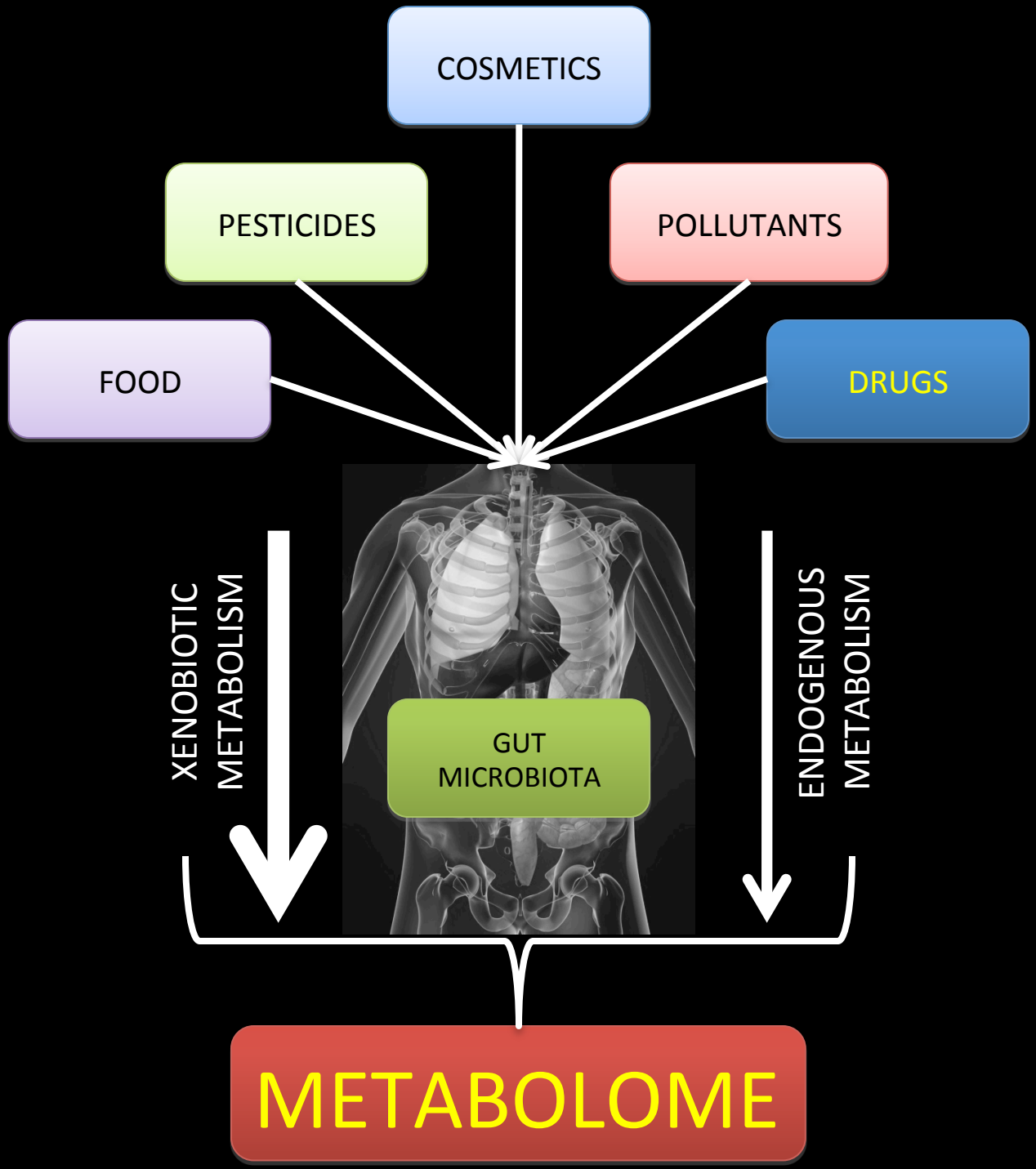
] SO WHAT?

- Toxicity of chloroform (check out ATSDR.CDC.GOV)

- Still made need to tailor specific extractions for lipid classes (hexane for TAGs or MTBE for Cer)
  - More detail checkout cyberlipid.org or lipidmaps.org

Metabolomics

Metabolomics is the systematic analysis of the unique chemical fingerprints left behind by specific cellular processes


COSMETICS
PESTICIDES
POLLUTANTS
FOOD
DRUGS
XENOBIOTIC METABOLISM
GUT MICROBIOTA
ENDOGENOUS METABOLISM
METABOLOME

Metabolomics

All “-omics” based scientific disciplines aim at the collective characterization and measurement of their particular constituent molecules

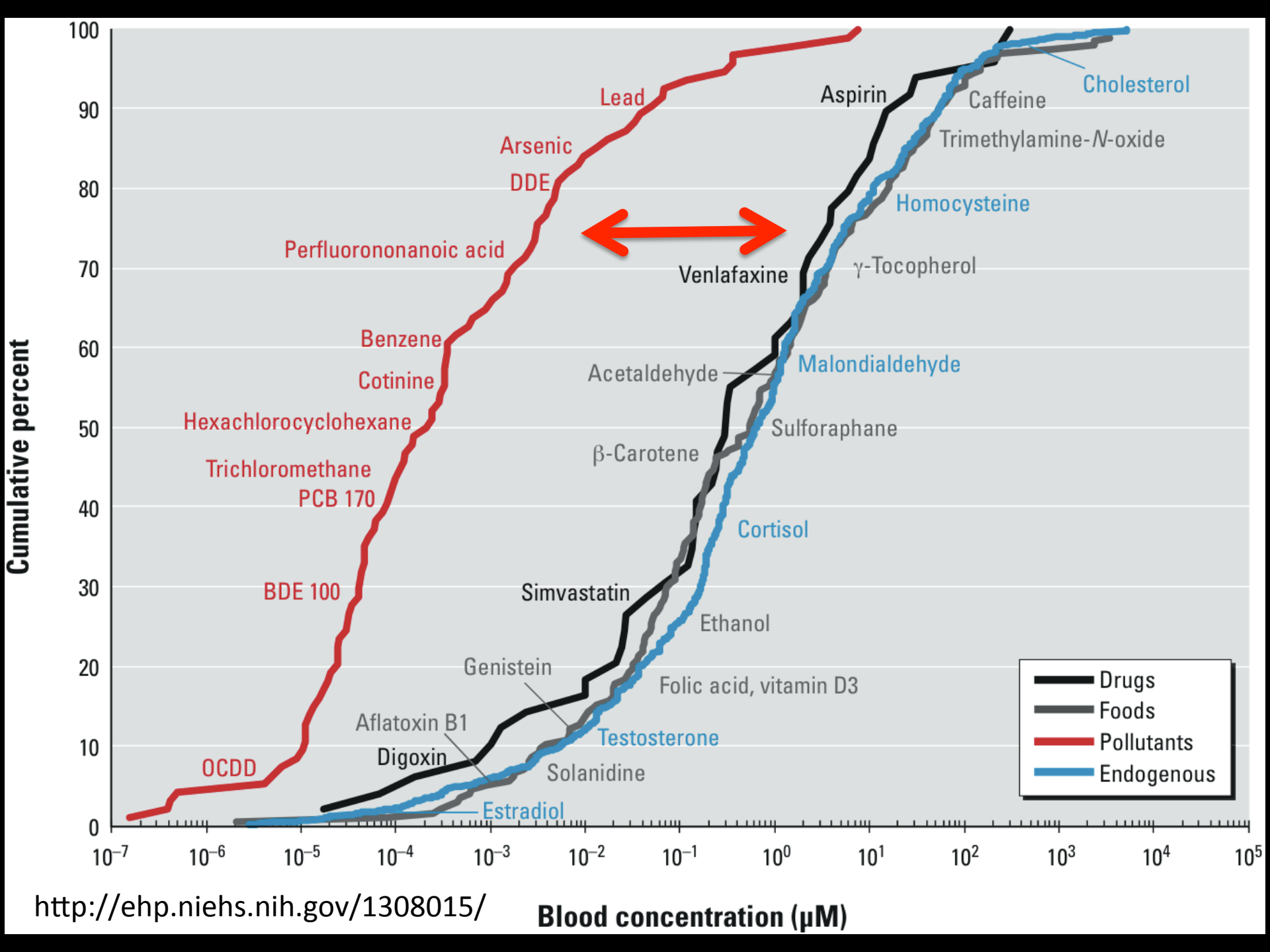
- A comprehensive approach to study complete pools of biological molecules

- Defines the structure, function and dynamics of an organism

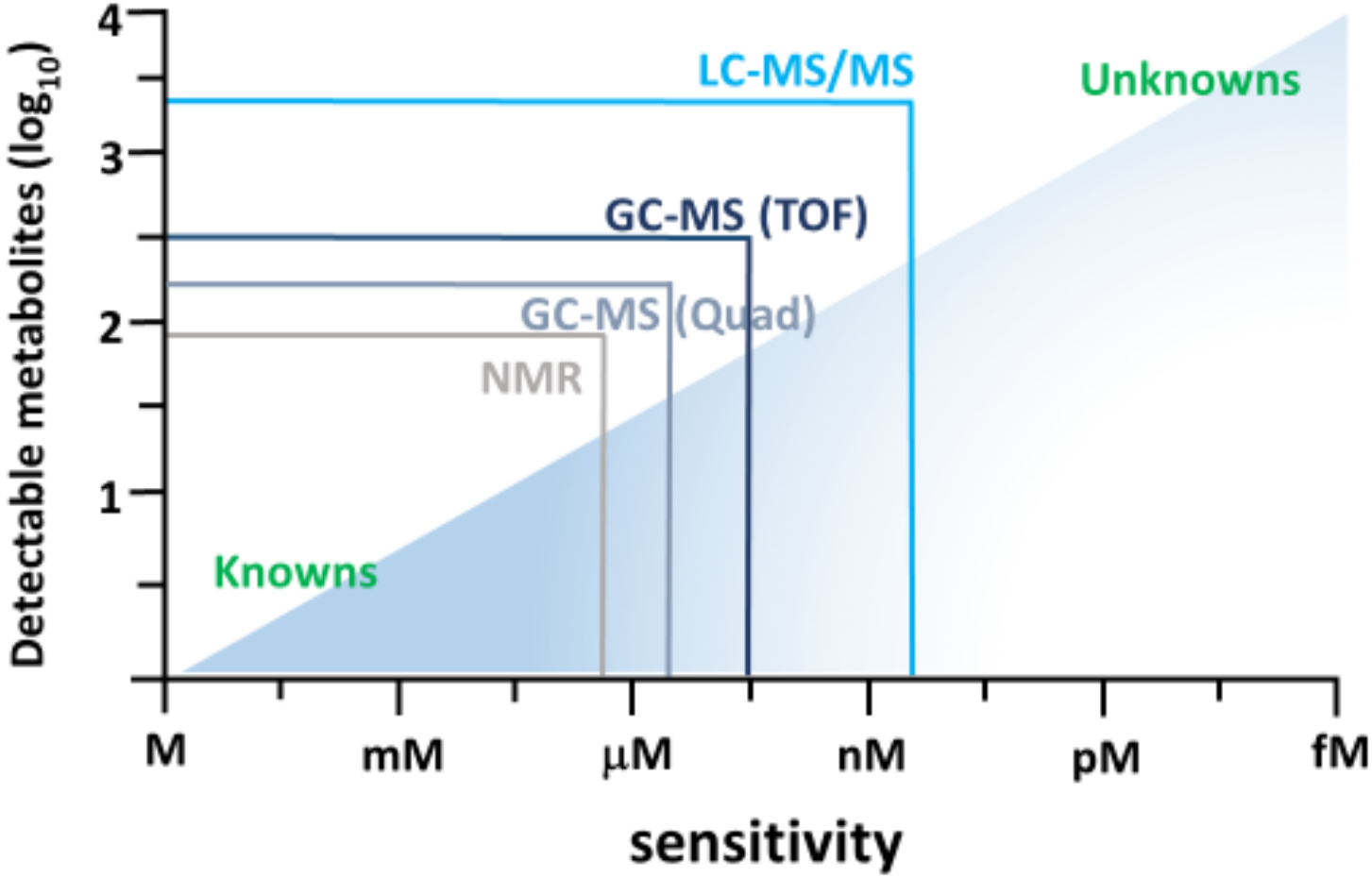
Metabolomics

Vast chemical diversity among small molecule metabolites has made extended coverage of the metabolome challenging

- Size (50 – 1500 Da)
- Concentration (pM – mM)
- Physicochemical properties (diverse log P values)
- Stereochemistry (distinct biological activity)



http://ehp.niehs.nih.gov/1308015/



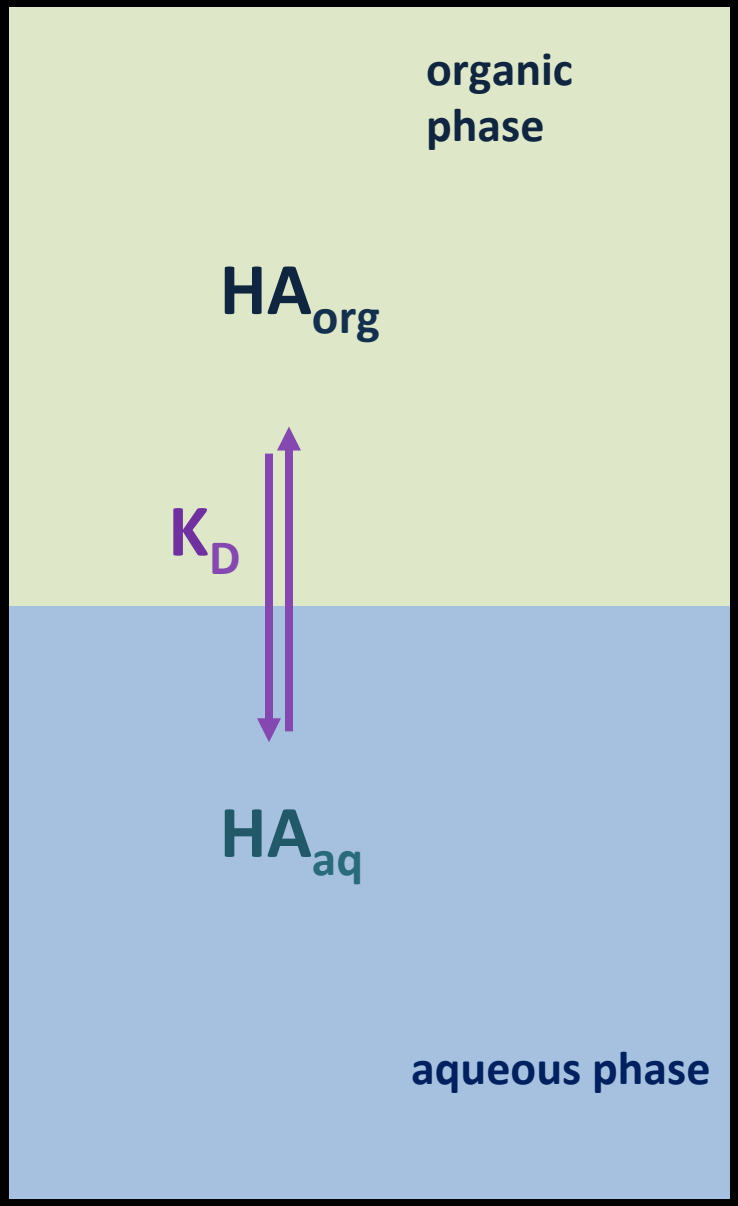
http://journal.frontiersin.org/article/10.3389/fimmu.2016.00044/full

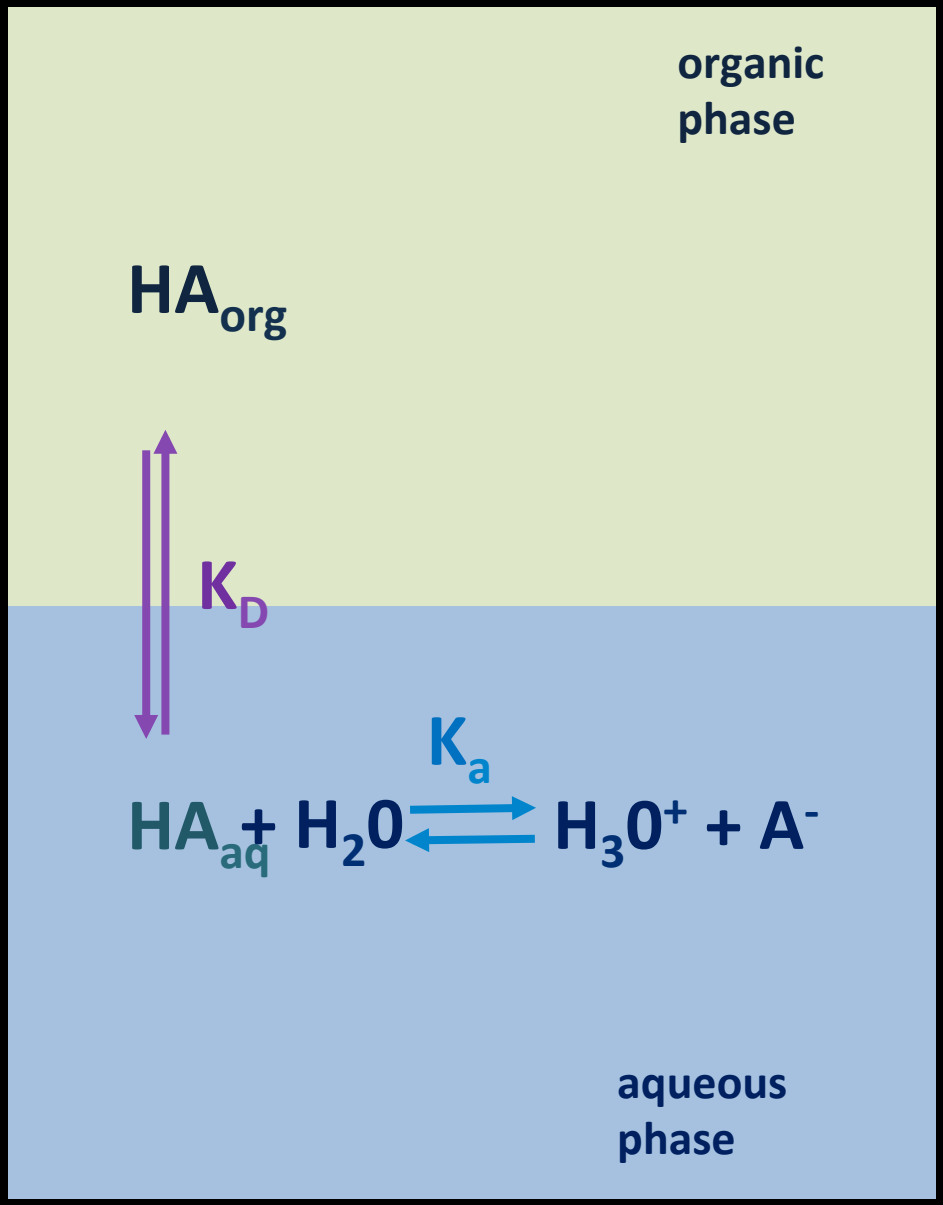
Metabolite Extraction

- Currently no analytical technique exists that is capable of measurement of all classes of cellular metabolites

- Metabolite extraction is a crucial step in any metabolomics study
  - Critical to both targeted and global based profiling strategies

- Optimized extraction methodology should fulfill several criteria:
  - Extract the largest number of metabolites
  - Unbiased and non-selective - physical or chemical properties of a molecule
  - Non-destructive - no modification of metabolites


organic phase
HA_{org}
K_D
HA_{aq}
aqueous phase


organic phase
HA_{org}
K_D
K_a
$HA_{aq} + H_2O \rightleftharpoons H_3O^+ + A^-$
aqueous phase

Separation of Metabolites

- Mass spectrometry usually requires some form of chromatographic separation
    - Most systems use either liquid or gas chromatography

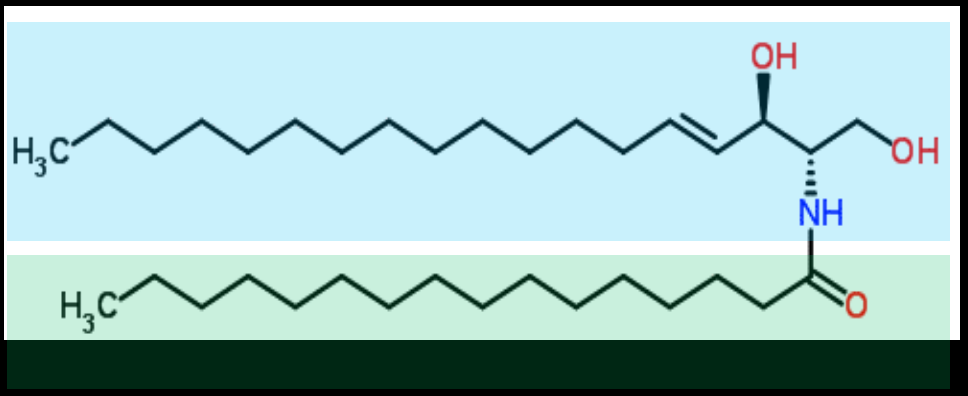
- Fractionation of sample components simplifies the resulting mass spectra while ensuring more accurate compound identification
    - Capacity factor (k) is critical to optimizing resolution
    - Increased resolution allows longer MS dwell times resulting in better signal/noise ratios

- Inadequate chromatographic separation of metabolites results in:
    - signal suppression – ion suppression
    - compromised metabolite quantification
    - reduced metabolite coverage

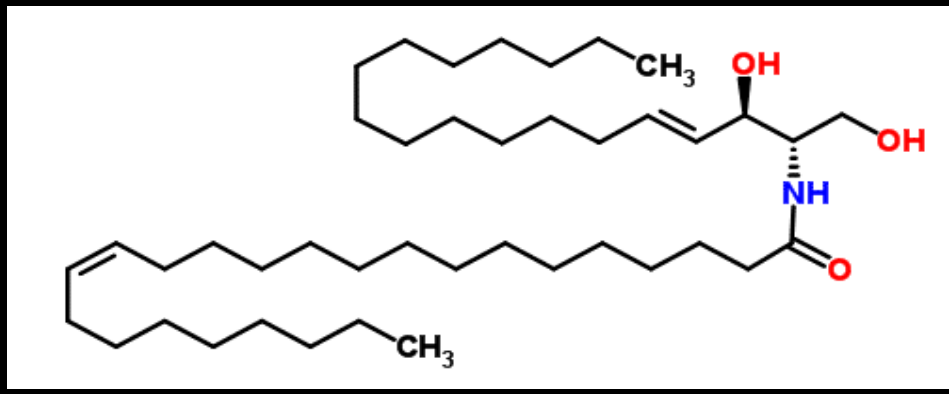
Ceramide Physicochemical Properties

- Ceramides are a family of waxy lipid molecules.
  - Name derived from the latin word: cera = waxy + amide
- Ceramides are comprised of:
  - sphingosine: 18 carbon unsaturated amino alcohol
  - fatty acid moiety – amide bond
- Ceramides are not water soluble:
  - Very hydrophobic
  - Confined to cellular membranes
  - Participate in lipid raft formation
  - >200 structurally distinct species have been identified in mammalian cells

Ceramide General Structure

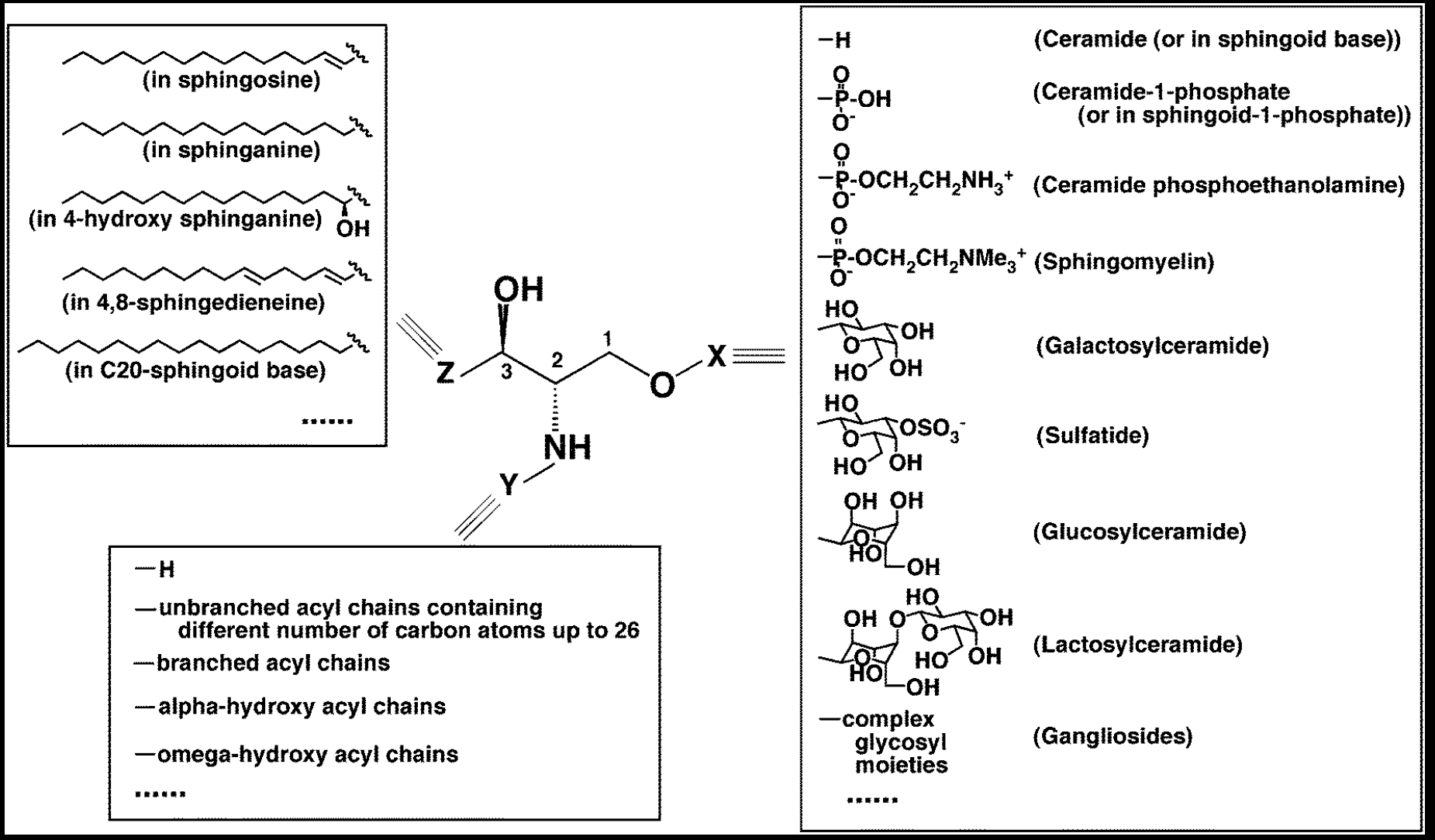


- Ceramide (d18:1/16:0)
- 2-amino-1,3-octadec-4-ene-diol
  - Amino alcohol (sphingoid) backbone
- Palmitic acid
  - Fatty acyl group



- **Ceramide (d18:1/24:1(15Z))**
- 2-amino-1,3-octadec-4-ene-diol
  - *Amino alcohol (sphingoid) backbone*
- 15-tetracosenoic acid
  - *Fatty acyl group*

Structures and Nomenclature



Ceramide Biochemistry

Ceramides are found in high concentration in the membrane of cells

- Structural component of the lipid bilayer
- Bioactive lipid - implicated in a variety of physiological functions including:
  - Apoptosis and cell growth arrest
  - differentiation and cell senescence
  - cell migration and adhesion

Ceramides are converted rapidly to more complex sphingolipids:

- Sphingomyelin
- Glycosylceramides
- Little accumulation observed
  - Except for the skin (50% of total lipids can be ceramides)

Biosynthesis of Ceramides

De novo biosynthesis

- Ceramide synthases couple sphinganine + long chain fatty acid to form dihydroceramide
- Double bond introduced into position 4 of the sphingoid base
  - ceramide synthases 5 and 6 generate are specific for palmitic acid
  - ceramide synthases 1 (brain and skeletal muscle) specific for stearic acid
  - ceramide synthases 2 specific for very long chain CoA-thioesters (C_{20}-C_{26})
  - ceramide synthases 3 unusual ceramides of skin & testes

Biosynthesis of Ceramides

Catabolism of complex sphingolipids:

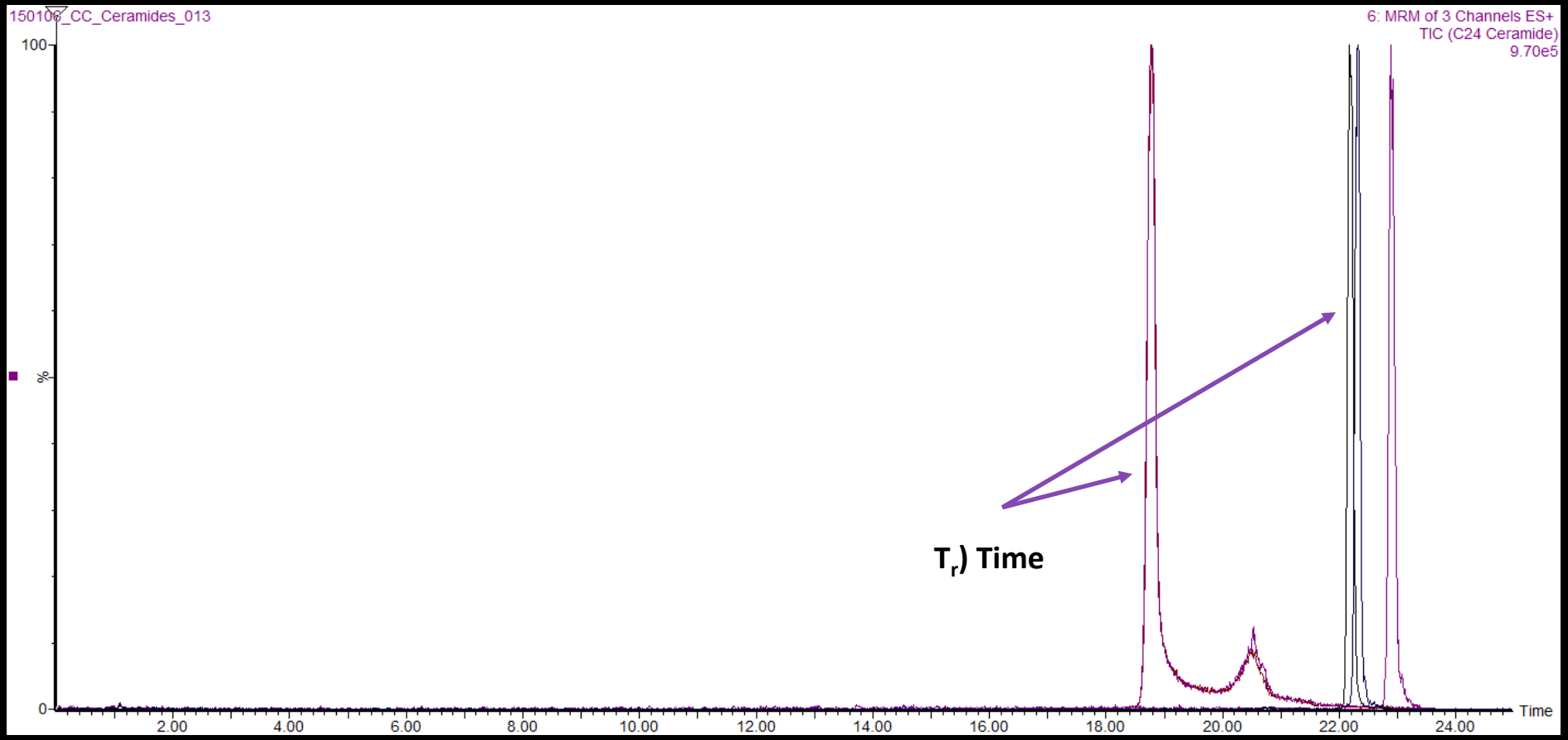
- **Sphingomyelinases/phospholipase C breakdown sphingomyelin in animal tissues**
- Many factors can stimulate the hydrolysis of sphingomyelin to produce ceramide:
  - Cytokines :TNF-a, IFN-g & various interleukins
  - 1,25-dihydroxy-vitamin D_3
  - endotoxin
  - nerve growth factor
  - ionizing radiation & heat

LC Method Development
Where to Start?

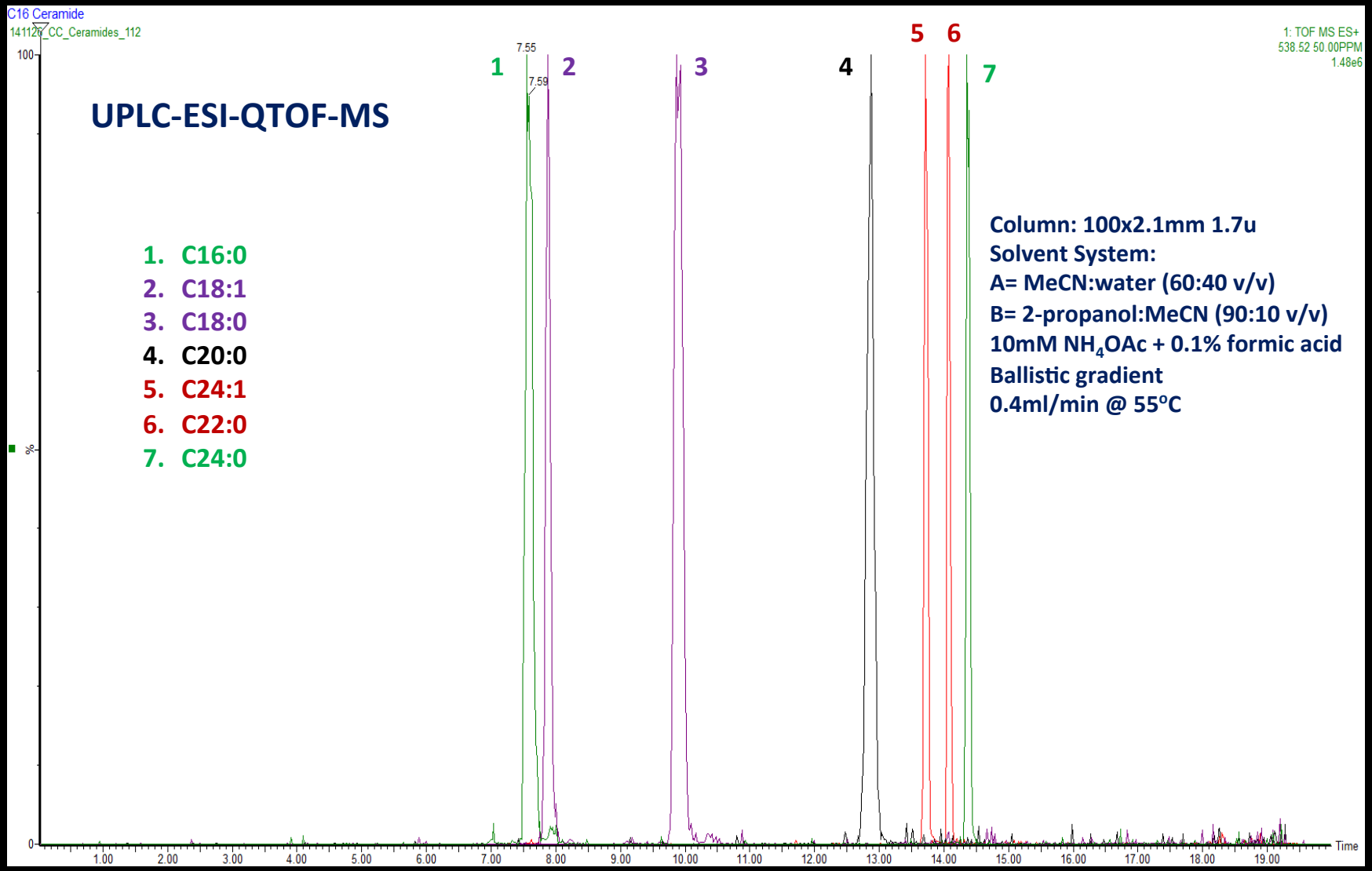
- Designing and optimizing an LC method involves choosing appropriate:
    1. Separation mechanism: NPC, RPLC, HILIC, size exclusion ion, exchange etc
    2. Column chemistry: C2, C4, C8, C18, cyanopropyl, phenyl, biphenyl, amide, SiOH etc
    3. Column properties: pore size, particle size & column dimensions
    4. Stationary and mobile phase combinations

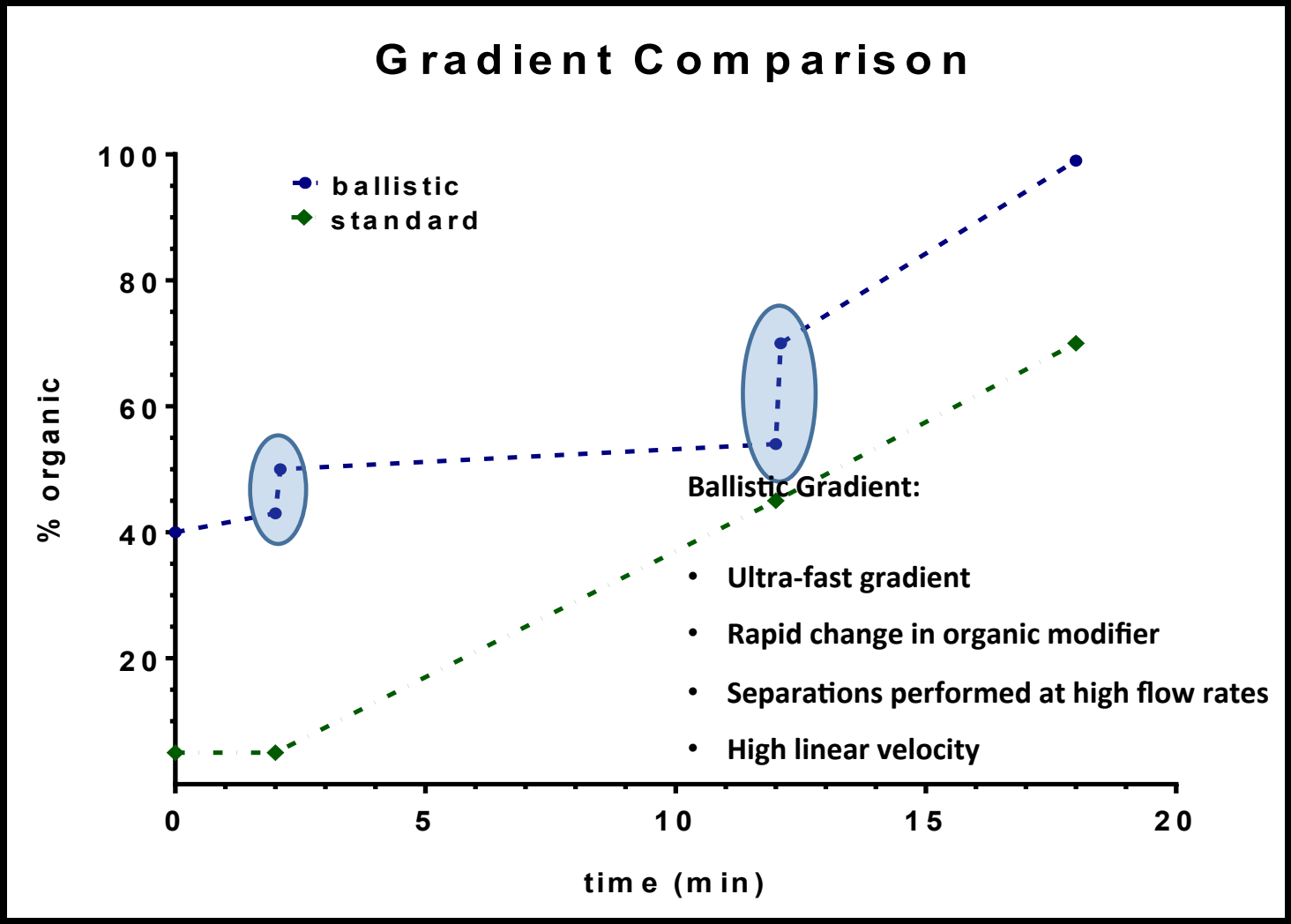
- Critical to optimizing the chromatographic efficiency, retention, resolution & selectivity of analytes

Ceramide Scouting Gradients on Waters BEH C18

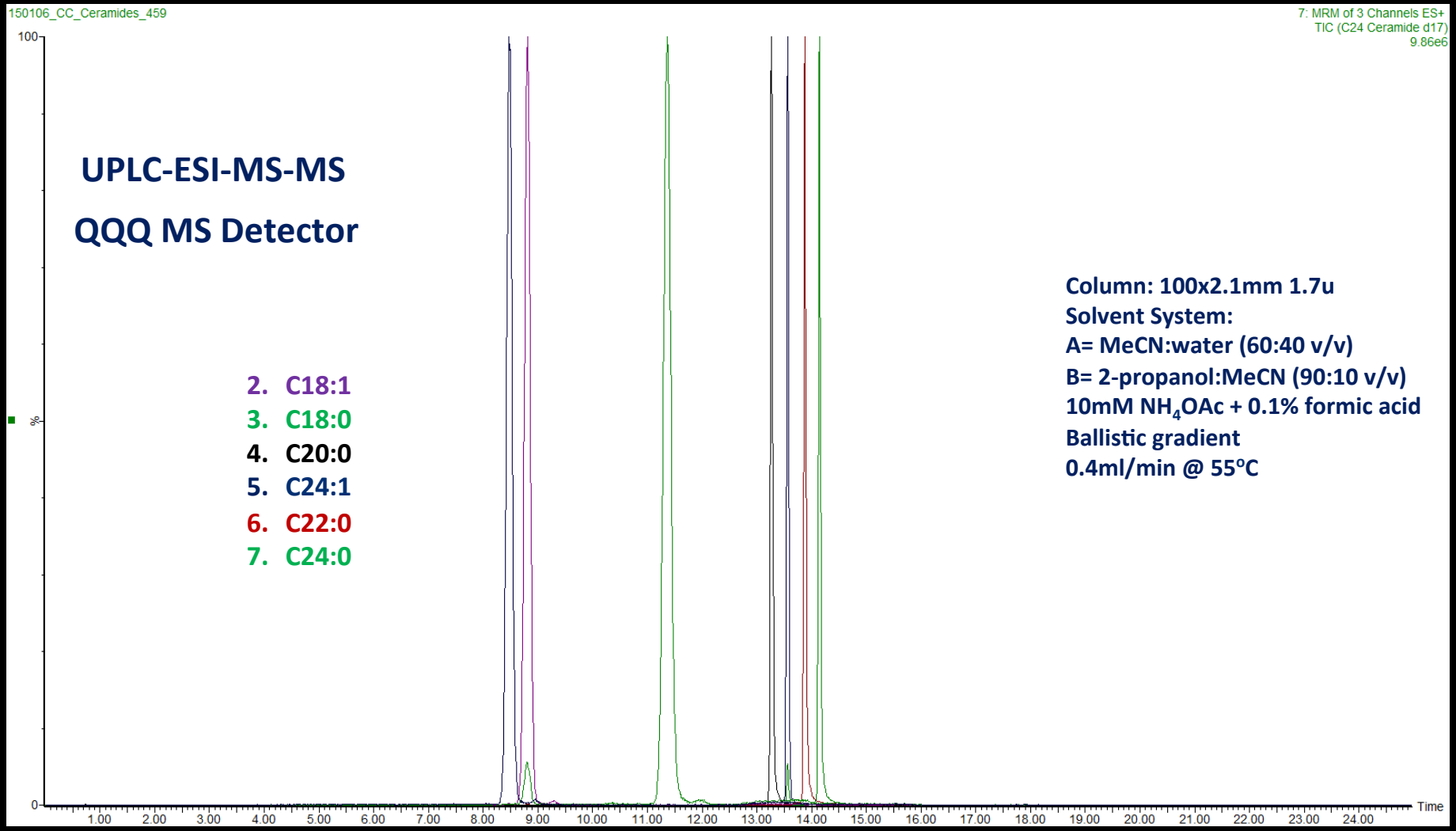


Fractionation of Ceramide Metabolites on Waters CSH C18 Column




Gradient Comparison
100
80
60
40
20
% organic
ballistic
standard
0
5
10
15
20
time (min)
Ballistic Gradient:
• Ultra-fast gradient
• Rapid change in organic modifier
• Separations performed at high flow rates
• High linear velocity

Fractionation of Ceramide Metabolites on Waters CSH C18 Column



Ceramide Extraction

Extraction protocols and LC-MS methods adapted from Shaner RL et al *JLR* 2009

- Add 50 mg of liver tissue to 50% aqueous methanol
  - Why not chloroform directly?
- Homogenize in Bertin Precellys at 6500 rpm with ~10 zirconium beads for 30 seconds

Ceramide Extraction – cont'd

- Add 1 mL of $CHCl_3$:MeOH (2:1, v/v) containing 20 µl of C17:0 internal standard solution (use 1 mM stock solution)
  - Why internal standard at this point?
  - Should we use glass or plastic? Does it matter?
  - What if you swap chloroform for hexane or isopropanol?
- Homogenize again and centrifuge at 18,000xg for 10 min to separate phases
- Transfer organic phase to a new tube (#2) and repeat extraction of left over material
  - Why repeat?

Ceramide Extraction – cont'd

- Combine organic phases and dry down in a vacuum centrifuge
- Solubilize residuals in 50 µl of $CHCl_3$:MeOH (2:1, v/v)
  - Why chloroform here?
- Saponification or acid hydrolysis of residuals to release ceramides

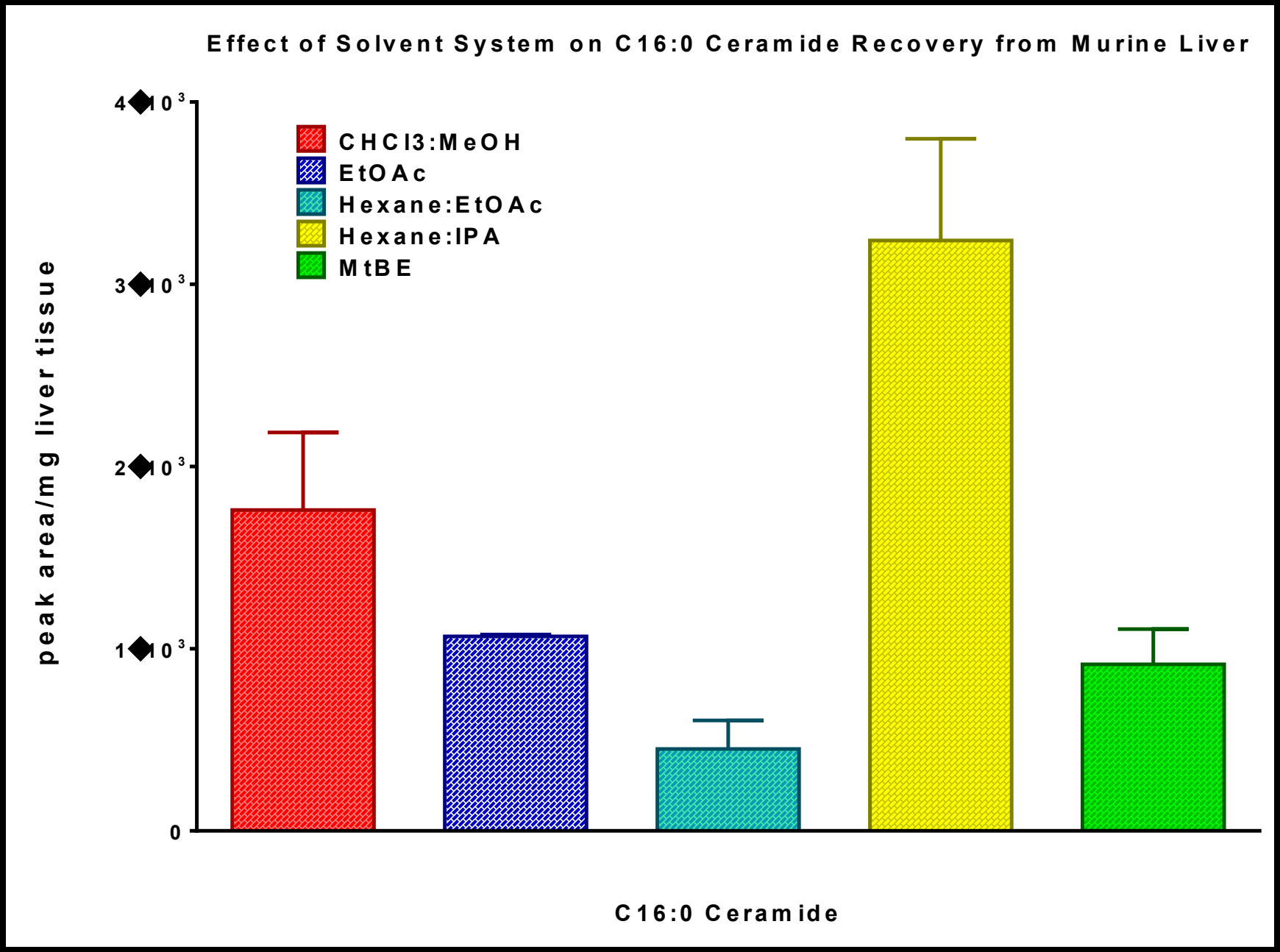
Ceramide Extraction – cont'd

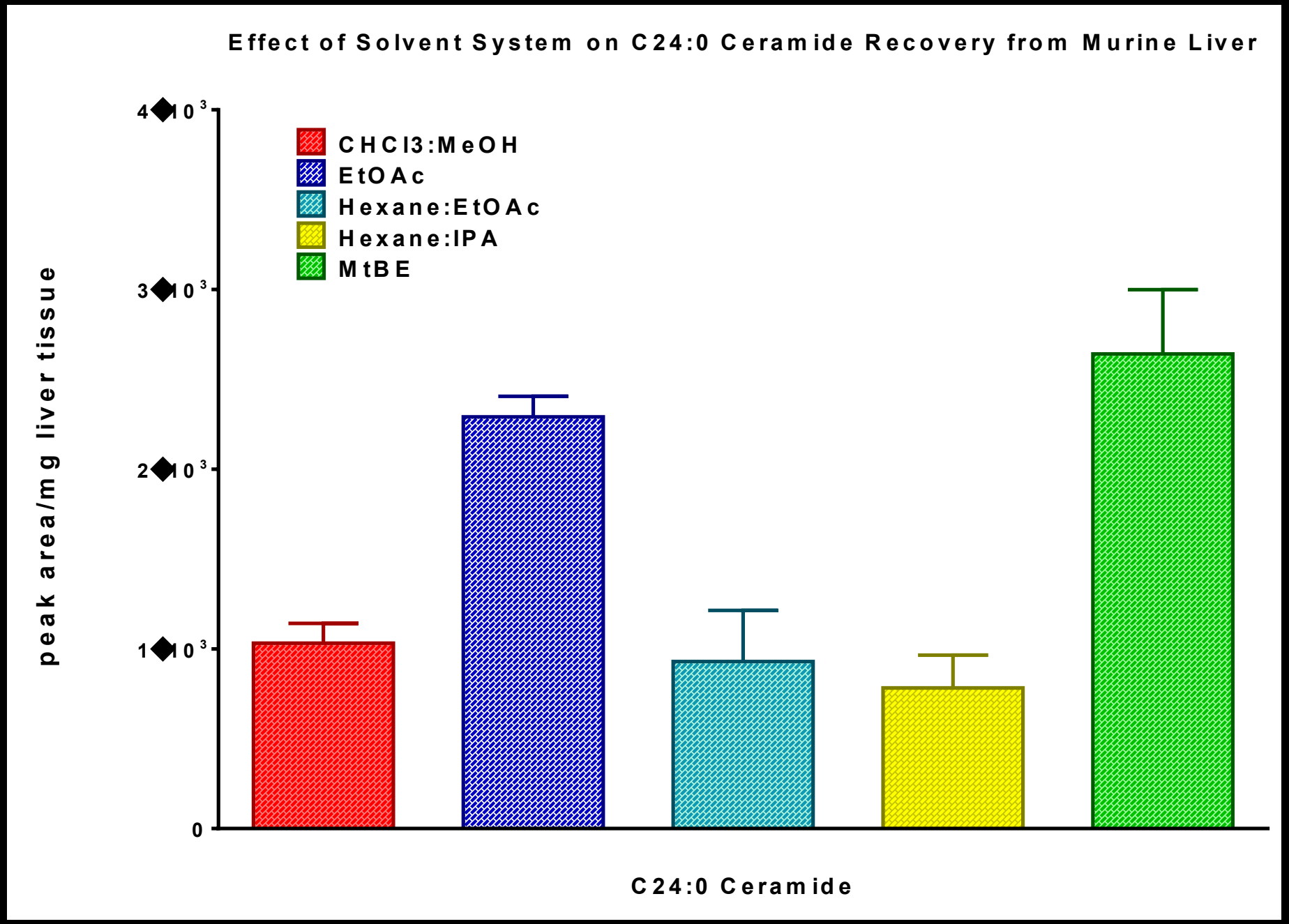
- Incubate residuals with 0.5 mL of 1M HCl in MeOH @ 50°C for 1 hr (or base for sapn)
- Cool samples and re-extract
- Solubilize with in 30 µl of $CHCl_3$:MeOH (2:1, v/v), sonicate for 5 minutes in sonicating water bath
  - Why sonicate?

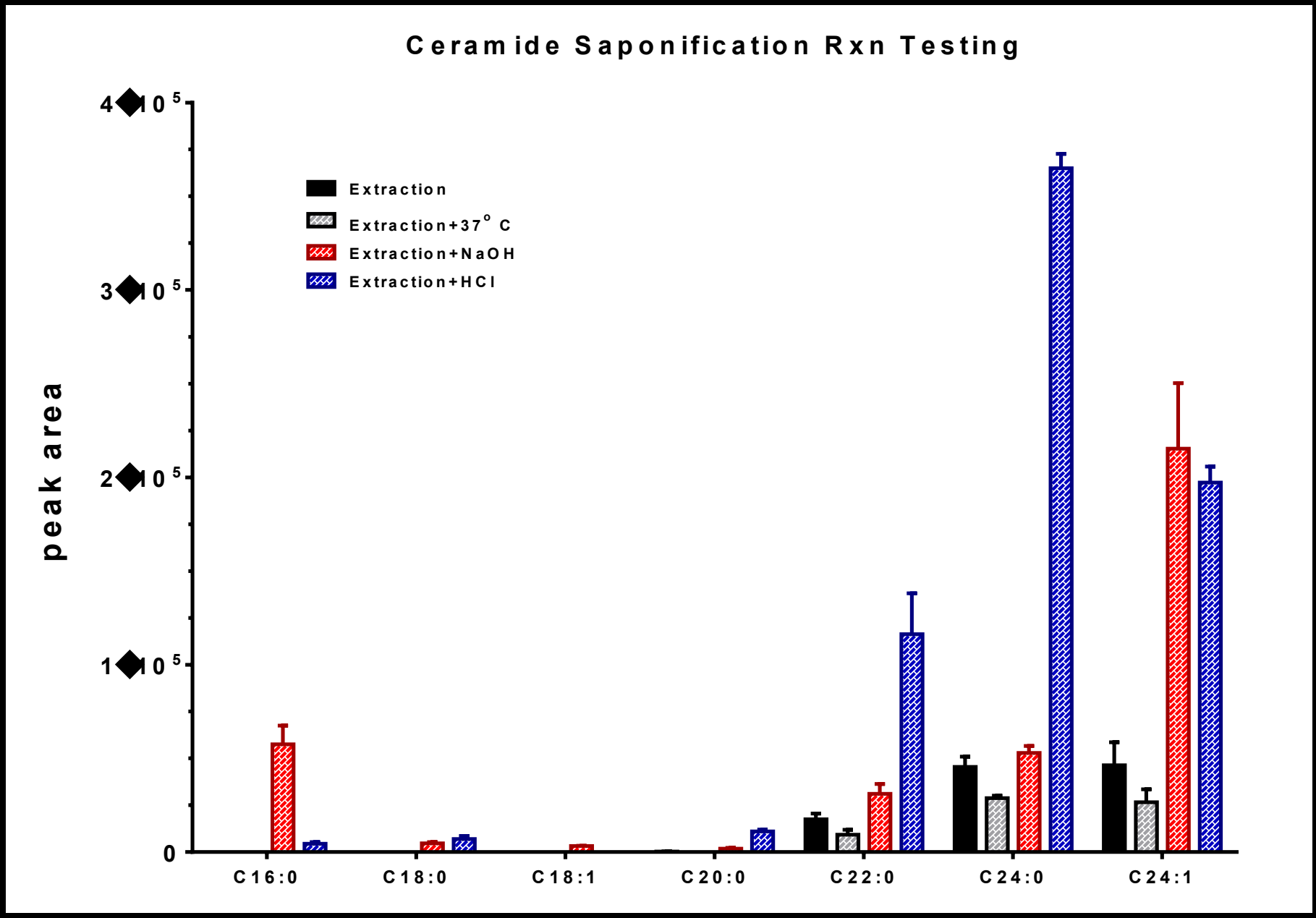
Ceramide Extraction – cont'd

- Dilute 10 fold with acetonitrile:isopropanol:water (1:1:1, v/v)

- Centrifuge to remove any particulates and transfer to autosampler tube

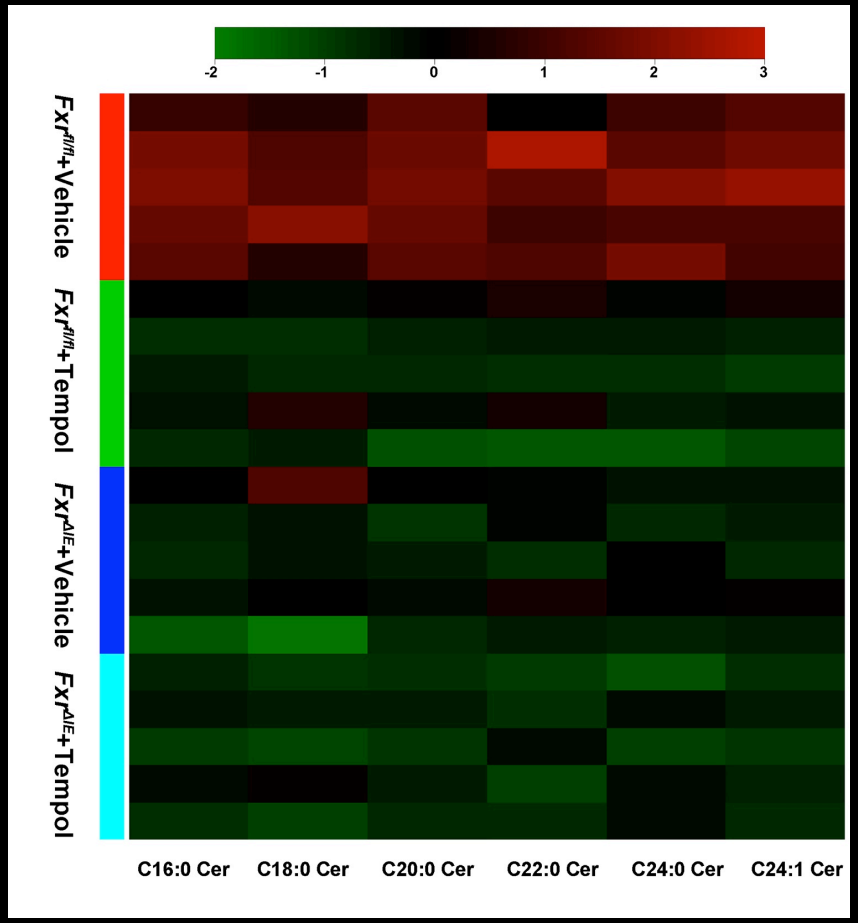

Effect of Solvent System on C16:0 Ceramide Recovery from Murine Liver
peak area/mg liver tissue
4◆10 3
3◆10 3
2◆10 3
1◆10 3
0
CHCl3:MeOH
EtOAc
Hexane:EtOAc
Hexane:IPA
MtBE
C16:0 Ceramide


Effect of Solvent System on C24:0 Ceramide Recovery from Murine Liver
peak area/mg liver tissue
4◆10 3
3◆10 3
2◆10 3
1◆10 3
0
CHCl3:MeOH
EtOAc
Hexane:EtOAc
Hexane:IPA
MtBE
C24:0 Ceramide

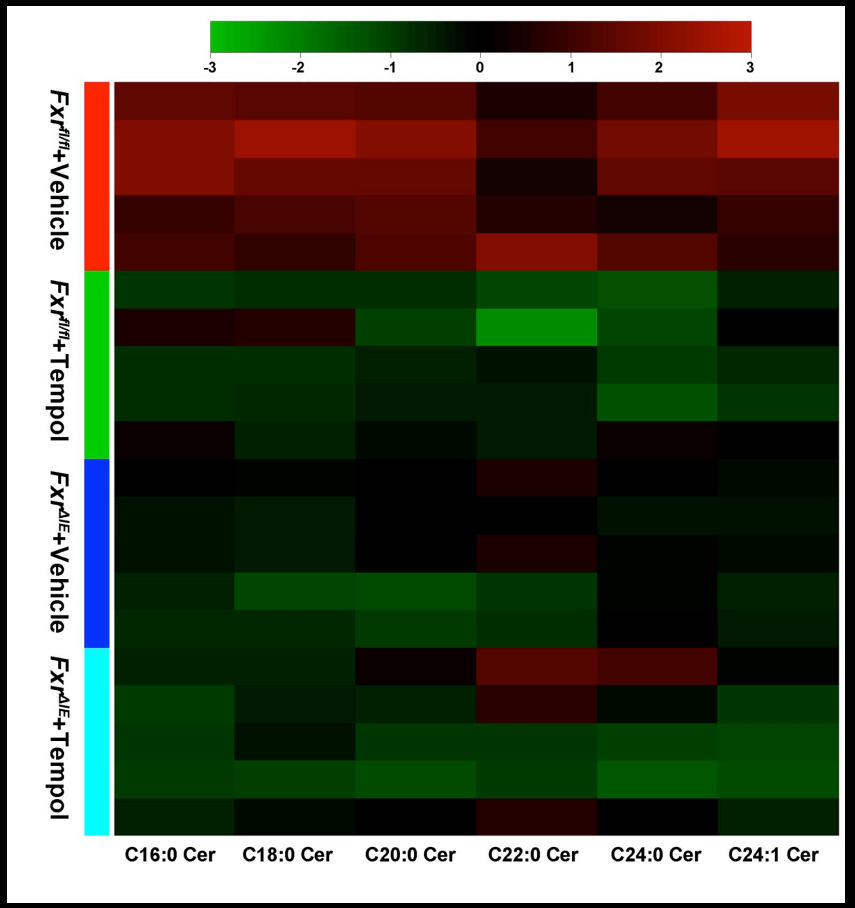

Ceramide Saponification Rxn Testing
peak area
4◆10 5
3◆10 5
2◆10 5
1◆10 5
0
Extraction
Extraction+37° C
Extraction+NaOH
Extraction+HCl
C16:0
C18:0
C18:1
C20:0
C22:0
C24:0
C24:1

Lipidomics Reveals Ceramides are Decreased in FXR Intestine-null Mice

Ileum



Serum



Other Classes of Metabolites

- Where might you have trouble extracting everything from a particular class of metabolites?

- Example: Are all bile acids the same in terms of general solubility in aqueous or organic solvents?

Matrix Effects

- Challenges with urine
  -
  -
- Challenges with blood, serum, or plasma
  -
  -
- Challenges with tissue
  -
  -

Conclusions

- Extraction protocols can impact metabolomic data sets considerably
- Solvent system composition and pH exhibit the most dramatic effects on metabolite recovery
  - The magnitude of these effects depend on metabolite class
  - Some classes of metabolites
- The number of extraction repetitions also plays a role in enhancing metabolite recovery
  - Tradeoff - longer sample prep time
  - Larger sample volumes to process (evaporate)

Conclusions

- Traditional RPLC methods can provide efficient separation of acyl-carnitine, bile acid and CoA thioester mixtures.
  - Advancements in hybrid particle technologies
  - Allowing for extremes in mobile phase pH and temperature – manipulate selectivity
  - Complex ligand stationary phase interactions

- HILIC methods are superior at separating highly polar metabolites.
  - Nucleotides and derivatives
  - Small polar metabolites – sugars, organic acids, amino acids, hydrophilic vitamins

Conclusions – cont'd

- There's no one "perfect" extraction or LC method available capable of efficiently extracting or resolving, respectively, all components or features in the metabolome

- Advanced column chemistries (amide, aminopropyl, biphenyl, graphite, phenyl-hexyl) and alternative chromatographic methodologies (HILIC) can provide enhanced coverage of the metabolome

Acknowledgments

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- Kris Krausz
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- Fei Li

NIEHS R01 ES022186

Metastars
www.metastars.org