Structure-Based Drug Design

BC530

Fall Quarter 2011

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Structural Biology and Drug Development
A marvelous partnership

A Structure of a Drug Target can initiate and accelerate drug development in many important ways:

I. **The Structure of the Target by itself shows immediate novel opportunities for drug design**
   e.g. The hexameric arrangement of helices in HIV gp41

II. **A Structure of a Target with a Substrate or Co-factor or TS Analog reveals which pockets can be filled by inhibitors and suggests which types of compounds to make**
   e.g. HIV protease:substrate complex
   Protozoan GAPDH:NAD complex
   Influenza Virus Neuraminidase Inhibitors

III. **Structures of the Target with Low MW-low affinity "fragments" show where fragments bind and how to modify and/or link fragments – to achieve higher affinity**
   e.g. "Fragment Cocktail crystallography"

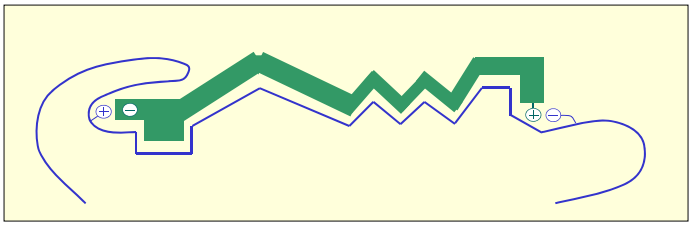
IV. **The structure of a compound found in a screen in complex with the Target reveals how the compound acts and how it can be modified for better affinity**
   e.g. NNRTI's and HIV Reverse Transcriptase
   Cyclosporin in complex with Calcineurin and Cyclophilin

V. **Structures of successive compounds bound to the same Target assist in understanding structure-activity relationships, binding modes and conformational changes : ITERATIVE STRUCTURE-BASED LEAD OPTIMIZATION.**
   e.g. Anti-Glaucoma drug targeting carbonic anhydrase

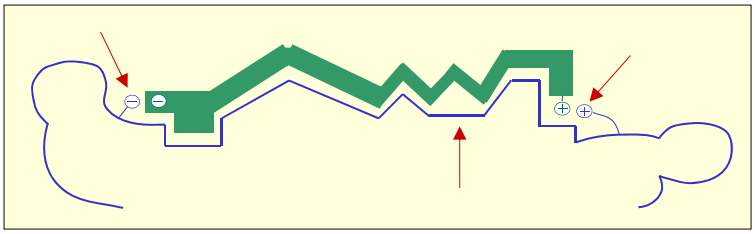
VI. **The structure of a Drug Candidate in complex with the Target can be helpful in devising strategies for modifications which MAINTAIN AFFINITY but improve e.g. drug bioavailability or decrease drug toxicity.**

VII. **The structure of a Drug:Target complex unravels the reasons for DRUG RESISTANCE**
   e.g. Gleevec and abl-src kinase

Simplified View of Structure-based Drug Design



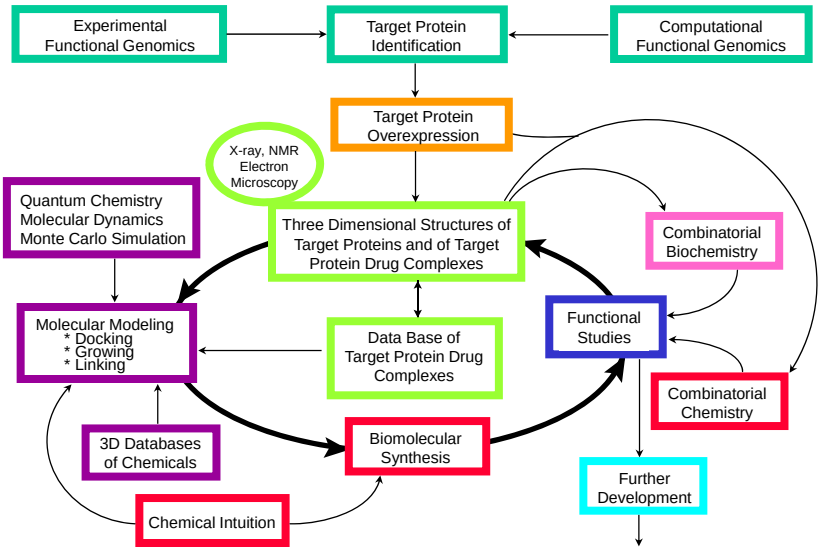
High Affinity for Drug Target



Low Affinity for Homologues of Drug Target

Selective Inhibition
Often, if not always, CRUCIAL

PROTEIN STRUCTURE BASED DRUG DESIGN CYCLE



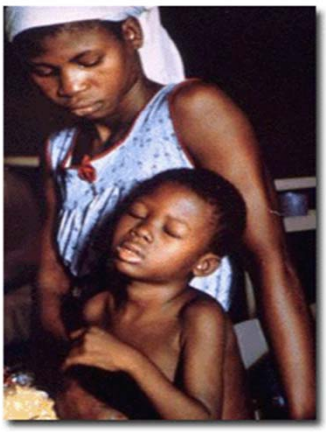
Drug Design

A case study

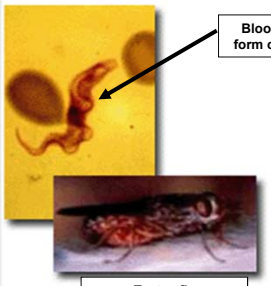
Structure-Based Inhibitor Design of the enzyme GAPDH from the sleeping sickness parasite, a "Trypanosomatid"

Sleeping Sickness

a.k.a "African Trypanosomiasis"



Lumbar puncture
for diagnosis of parasites in CNS



Blood stream
form of parasite

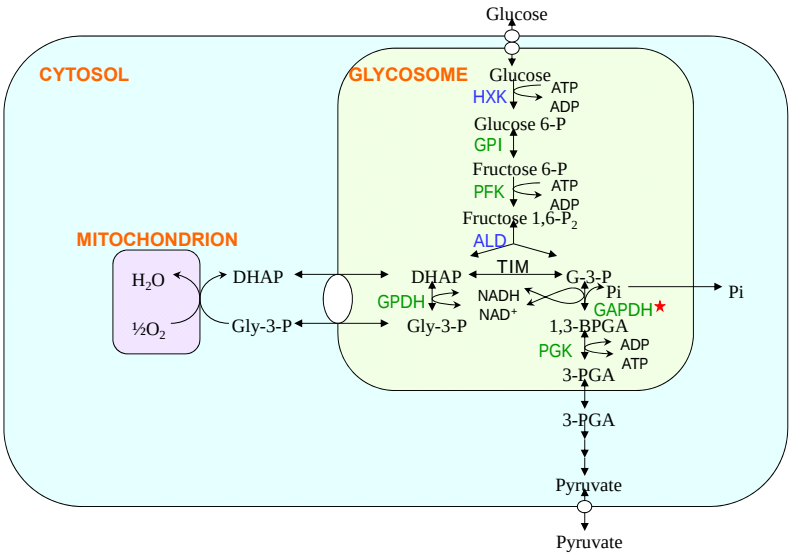
Tsetse fly

Sleeping sickness is caused by a unicellular eukarytote: *Trypanosoma brucei* – a "Trypanosomatid"
Other pathogenic trypanosomatids are whole set of *Leishmania* species.
These cause a spectrum of different tropical diseases, called "leishmaniasis".
Many enzymes in *Trypanosoma brucei* and *Leishmania* species are very similar in amino acid seqeunce.

With thanks to Wes Van Voorhis

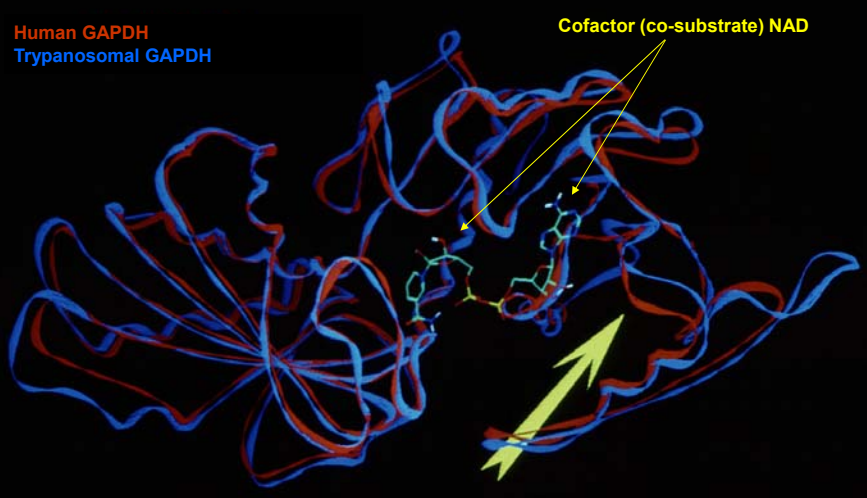
Glycolytic enzymes are critical for the blood stream form of *Trypanosoma brucei*

(ONLY in this group of parasites most of the glycolytic enzymes are sequestered in a unique organelle: the glycosome)



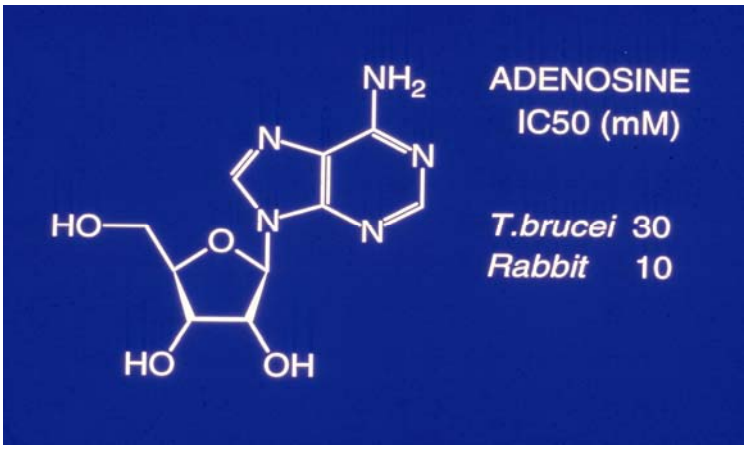
PTS1 signal
PTS2 signal

Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) from the Sleeping Sickness Parasite and the human host



Note the difference in conformation near the ribose of the NAD cofactor in the homologous proteins of host and parasite.

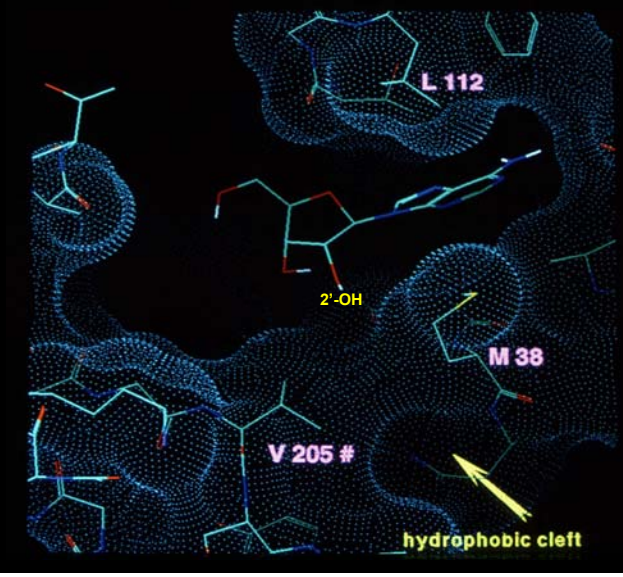
Adenosine – the starting point



- Adenosine is part of the cofactor (co-substrate) NAD of the enzyme GAPDH
- It is by itself a poor inhibitor of mammalian and *T. brucei* parasite GAPDH
- Moreover, it inhibits the sleeping sickness parasite enzyme slightly *worse* than the mammalian enzyme.

Glyceraldehyde-3-phosphate dehydrogenase (GAPDH)

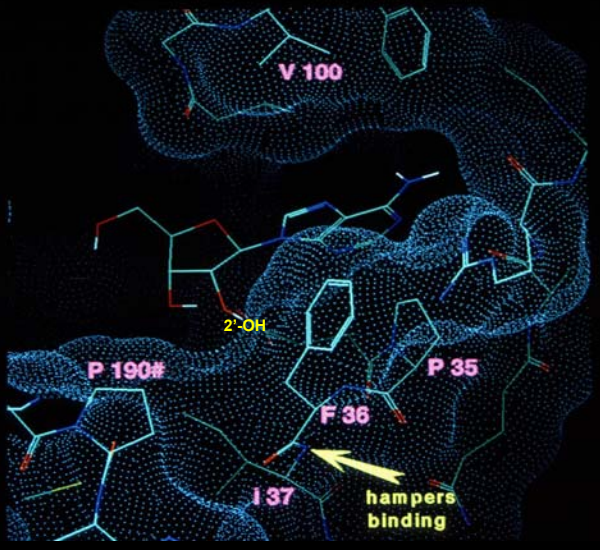
Sleeping sickness parasite GAPDH : Hydrophobic Groove near 2'OH of Adenosine



Fred Vellieux
Christophe Verlinde

Glyceraldehyde-3-phosphate dehydrogenase (GAPDH)

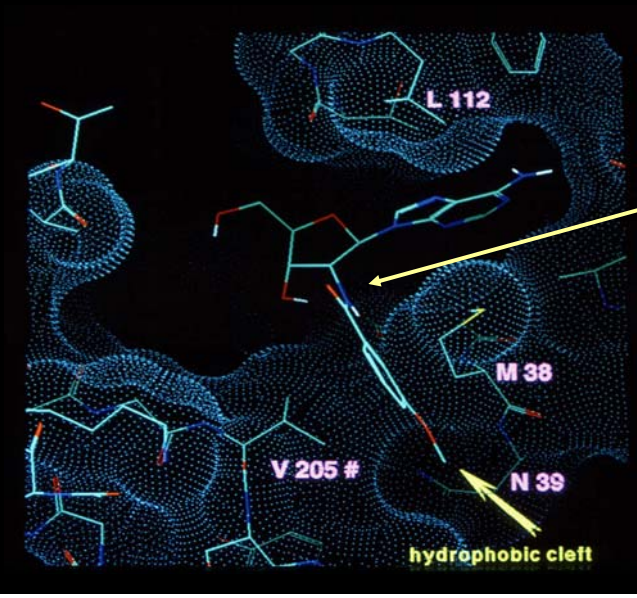
Human GAPDH : NO groove near 2'OH of Adenosine



Randy Read
Christophe Verlinde

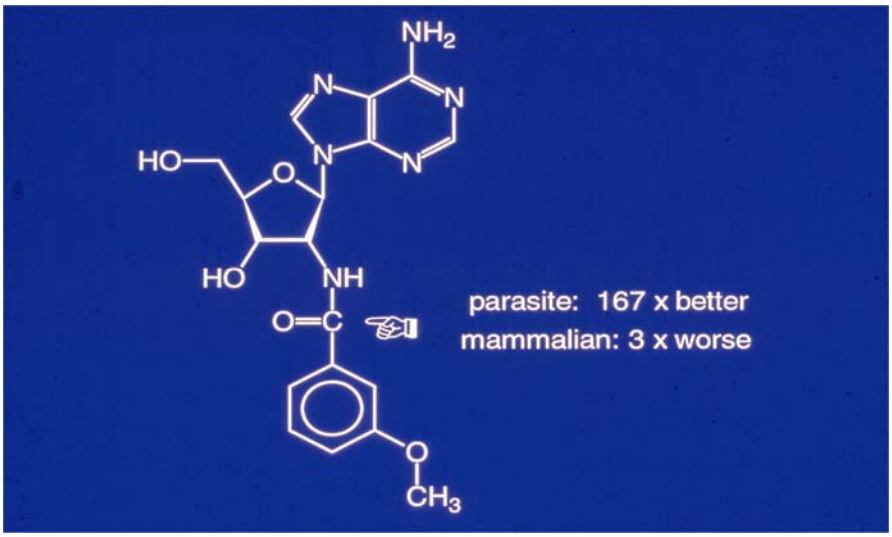
Glyceraldehyde-3-phosphate dehydrogenase (GAPDH)

Sleeping Sickness parasite GAPDH : Substituent Modeled in Hydrophobic Groove near 2'OH of Adenosine



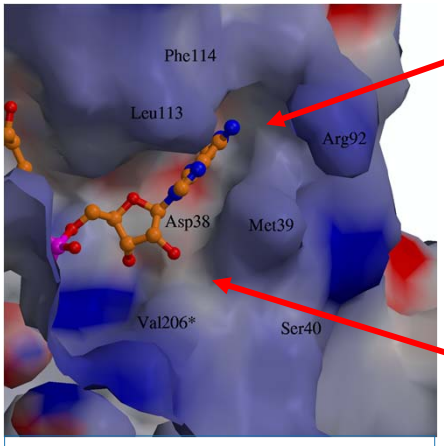
Christophe Verlinde

Selectivity of Structure-based Designed GAPDH Inhibitors



Selectivity changes of 2'-OH substituted compound *versus* adenosine

Exploring additional hydrophobic grooves near the adenosine binding pocket of *Leishmania mexicana* GAPDH



Surface of *L. mexicana GAPDH with NAD bound.**

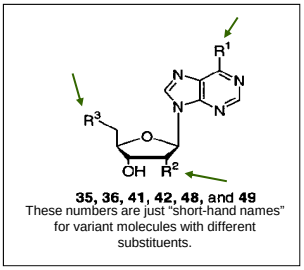
Hydrophobic Groove

Structure leads to "Targeted Combinatorial Chemistry" to fill the grooves optimally

Hydrophobic Groove

•Note: *Leishmania mexicana* GAPDH is ~77% sequence identical to *Trypanosoma brucei* GAPDH and all residues in the region of interest are identical in these two pathogenic "Trypanosomatids". So these two enzymes are used interchangeably.

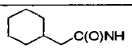
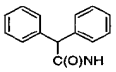
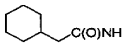
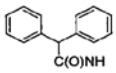
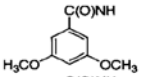
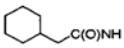
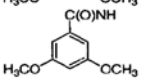
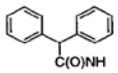
Inhibition of *L. mexicana* GAPDH by Adenosine Derivatives



35, 36, 41, 42, 48, and 49
These numbers are just "short-hand names" for variant molecules with different substituents.

Principle:

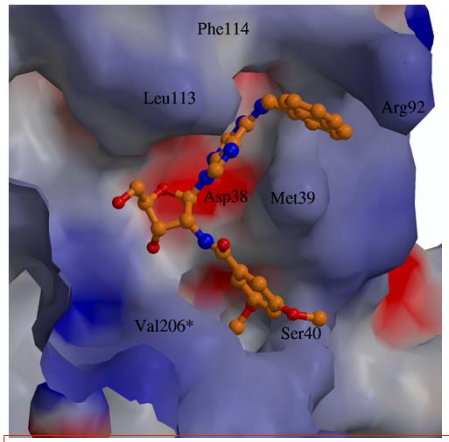
Make a diverse set of inhibitors by different substituents at three positions R^1, R^2 and R^3 of a so-called "scaffold molecule" (shown above).

Compound	R^1	R^2	R^3	IC_{50} (μM)
35	NH_2	OH		250
36	NH_2	OH		250
41		OH		inactive
42		OH		inactive
48	NH_2			100
49	NH_2			60

[a] Inactive = inactive at 50 μM.

Michael Gelb and coworkers, Wes Van Voorhis, Fred Buckner

Inhibition of *L. mexicana* GAPDH by Adenosine Derivatives



Crystal structure of L. mexicana GAPDH with "NMDBA"

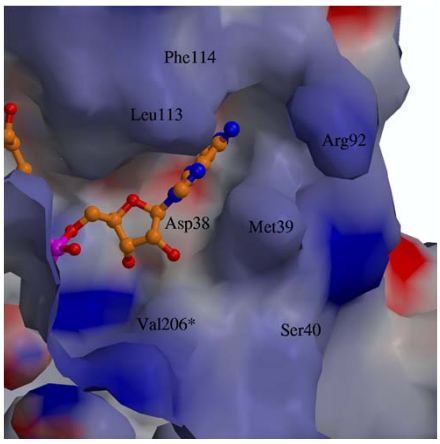
Clearly visible is the selectivity cleft between Met39 and Val206* (from the neighboring monomer), with the dimethoxybenzamido group of NMDBA inserted into it.

The surface has been color coded according to the electrostatic potential. Red represents negative potential and blue positive potential.

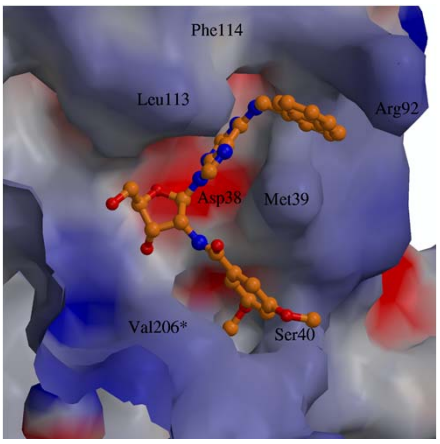
"NMDBA": A new inhibitor with 10^5-fold (!) affinity gain compared to the initial inhibitor adenosine

Stephen Suresh Antonysami

Flexibility in the structure of *L. mexicana* GAPDH

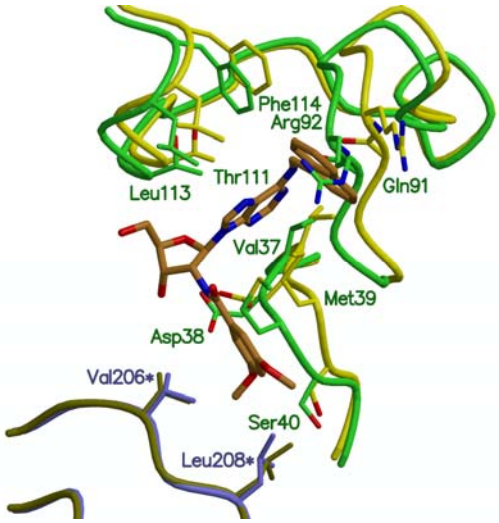


LmGAPDH + NAD



LmGAPDH + NMDBA

Flexibility in the structure of *L. mexicana* GAPDH



GAPDH in complex with NAD: green and violet
GAPDH in complex with TNDBA: yellow and gold
Only TNDBA shown

The figure illustrates the displacements of the protein atoms at the inhibitor binding site. In particular, the movement of Met39 effects expansion of the selectivity cleft, and this motion propagates to the other atoms involved in inhibitor binding.

Adaptation of the protein to a ligand is a very common, yet stilll an often surprising, event.

Influenza Virus Neuraminidase Inhibitors

A classic example of
Structure-Based Drug Design (SBDD)
on the basis of a

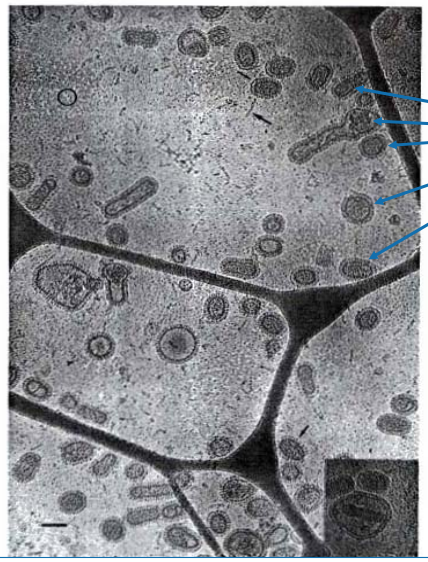
Enzyme-Transition State Analog Complex

&

affinity gain by increasing electrostatic interactions

INFLUENZA VIRUS

Influenza Virus has two surface proteins: haemagglutinin (H) and neuraminidase (N).



Flu Virus is clearly "pleiotropic", i.e. occurs in different shapes.

Well underfocused electron micrograph of an unstained, frozen, hydrated specimen of A/X31 influenza virus. The bar in the lower left represents 1000 Å.

Influenza Virus Neuraminidase Inhibitors

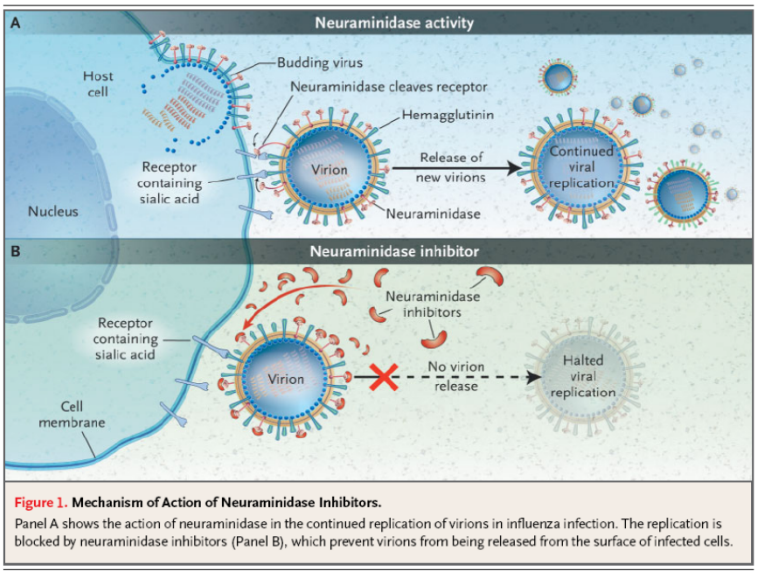
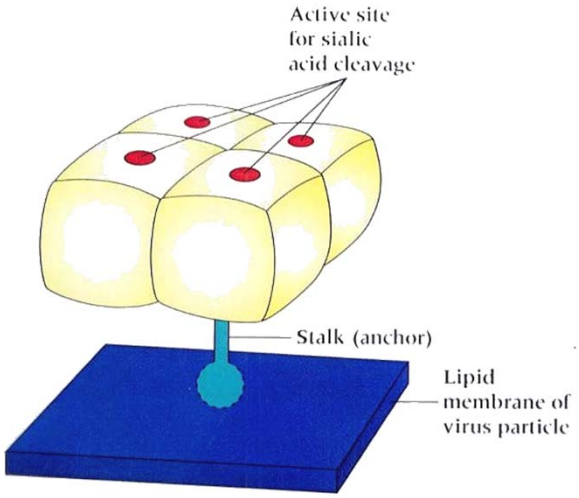


Figure 1. Mechanism of Action of Neuraminidase Inhibitors.
Panel A shows the action of neuraminidase in the continued replication of virions in influenza infection. The replication is blocked by neuraminidase inhibitors (Panel B), which prevent virions from being released from the surface of infected cells.

Moscona, A., N. Engl. J. Med 353: 1363-1373 (2005).

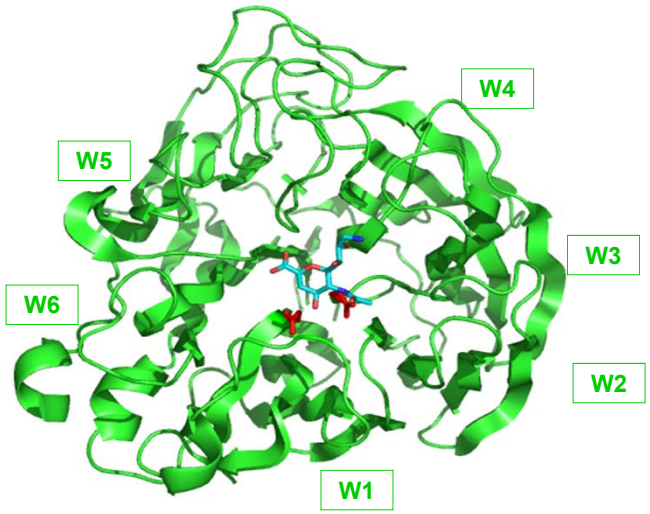
Influenza Virus Neuraminidase.



The enzyme neuraminidase plays a key role in the release of new viruses from the host cell surface.

Inhibition of neuraminidase activity appeared to be a good way to decrease the severity of a flu infection.

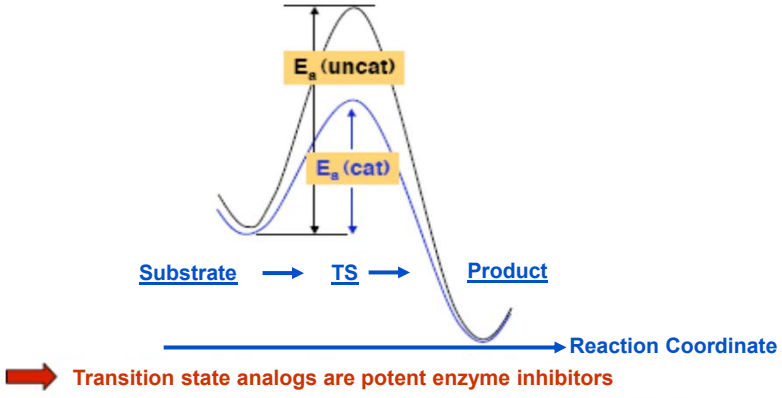
The Three-dimensional Structure of a Single Subunit of Influenza Virus Neuraminidase



Wn = n-th 4-β-stranded "propeller"

SMITH et al, PROTEIN SCI. 10: 689 (2001) – PDB-code 1F8D.

Enzyme often catalyze reactions by preferential binding of the transition state *vs* the ground state

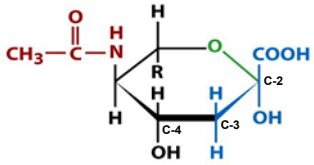


Transition state analogs are potent enzyme inhibitors

TS = Transition State

Modified from Carolyn R. Bertozzi - website: http://grtc.ucsd.edu/lecture42.pdf

The substrate of neuraminidase



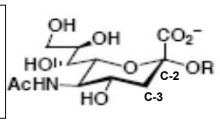
N-Acetylneuraminic acid
(pyranose form)

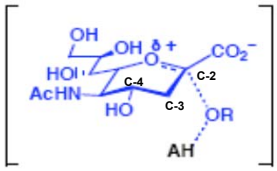
Sialic Acid ≡ N-acetylneuraminic Acid (VVP 2nd Ed. p 213)

(A complex sugar, attached to quite a few human cell surface proteins)

The Reaction catalyzed by neuraminidase

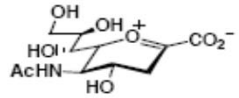
Substrate (Sialic Acid bound to a protein via the 2-OH)

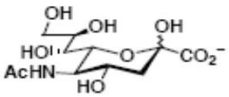




Transition State:

With the Ring-O, the C-2, the Carboxyl carbon and the C3 approximately in one plane.





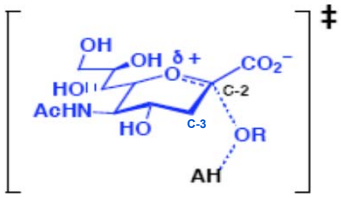
Product

(Free Sialic Acid)

Sialic acid = N-ACETYL-NEURAMINIC ACID (VVP 2nd Ed. P. 213)

Modified from Carolyn R. Bertozzi - website: http://grtc.ucsd.edu/lecture42.pdf

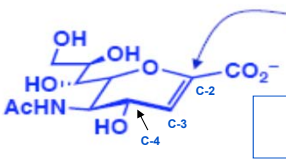
Design of Transition State Analog neuraminidase inhibitors



Transition State

Features:
- Planarity at C-2
- Buildup of + charge

DANA
$K_I = 10^{-6}$ M
Also inhibits human neuraminidase



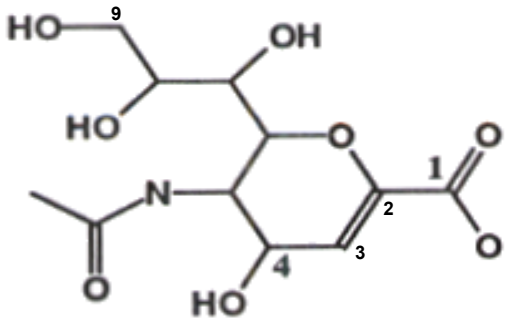
Transition State Analog

DANA ≡
2-DEOXY-2,3-DEHYDRO-N-ACETYL-NEURAMINIC ACID

Adapted from Carolyn R. Bertozzi - website: http://grtc.ucsd.edu/lecture42.pdf

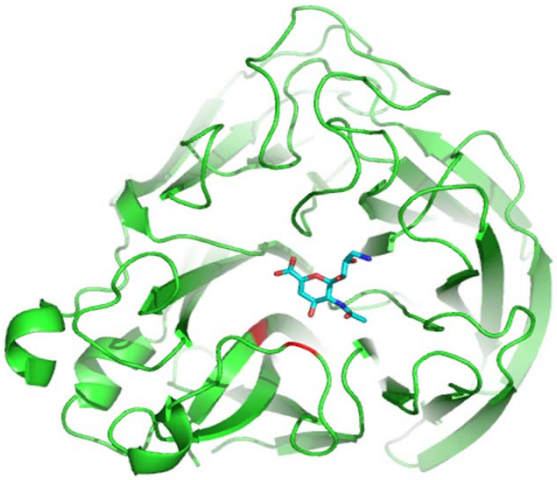
The Starting Point

The Transition State Analog (TSA) DANA



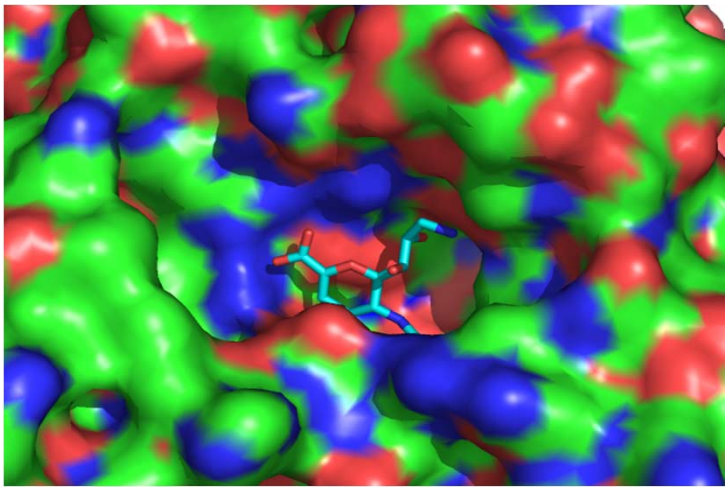
DANA

Influenza Virus Neuraminidase in complex with 9-amino-DANA



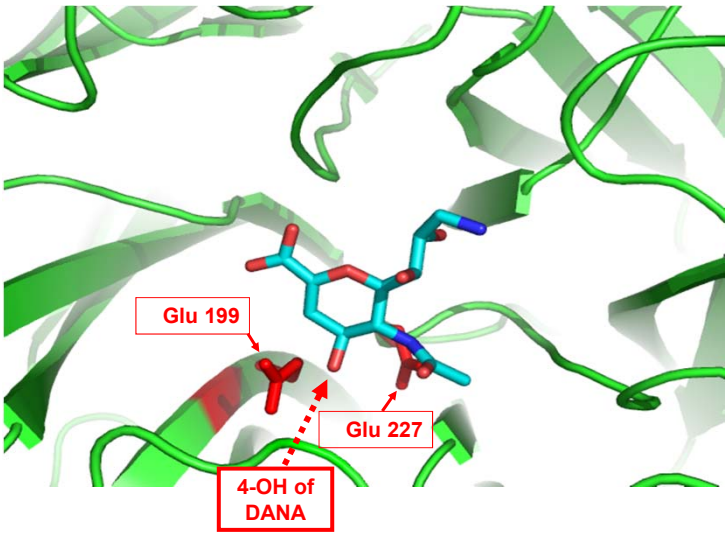
9-amino-DANA =
9-AMINO-2-DEOXY-2,3-DEHYDRO-N-ACETYL-NEURAMINIC ACID
(The 9-amino group is irrelevant for the drug development story)

Influenza Virus Neuraminidase in complex with 9-amino-DANA



9-amino-DANA sits clearly in a pocket.
This is the active site of neuraminidase

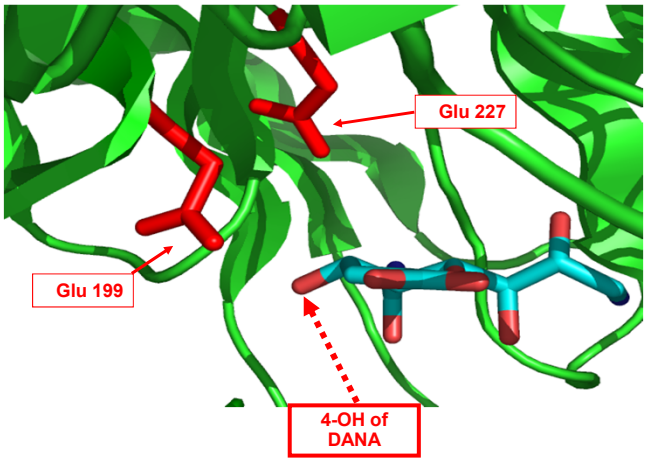
Influenza Virus Neuraminidase in complex with 9-amino-DANA



View of two key Neuraminidase residues near the 4-OH of 9-amino-DANA

Influenza Virus Neuraminidase in complex with 9-amino-DANA

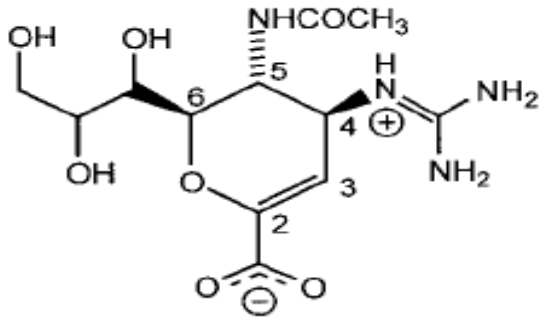
Close-up and 90 degrees rotated



TWO NEGATIVELY CHARGED CARBOXYLATES ARE QUITE CLOSE TO THE 4-OH !!!!!

Compound made: 4-guanidino-DANA

A guanidino substituent at the 4-position instead of a hydroxyl



Does it indeed live up to the expectations?
I.e. of being a better inhibitor than DANA?

Von Itzstein et al, Nature 363:419 (1993)

Inhibitory Properties of modified 4-guanidino-DANA

Based on the structure of the TSA DANA in complex with influenza virus neuraminidase, the compound 4-guanidino-DANA was designed and synthesized.

The K_i-values (in M) were as follows:

	Flu Neura	Human Neura
DANA	1×10^{-6}	1.2×10^{-5}
4-guanidino-DANA	2×10^{-10}	1×10^{-3}

By changing one single functional group:

The affinity for the target flu enzyme was enhanced by a factor of ~10,000;

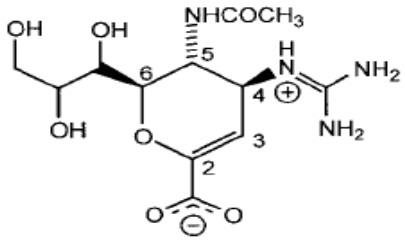
The affinity for the human homologous enzyme was decreased by a factor of ~100.

The selectivity was improved by a factor ~1,000,000!!!

Von Itzstein et al, Nature 363:419 (1993)

Properties of 4-guanidino-DANA

Zanamivir (Relenza)



Zanamivir

This compound is obviously very hydrophilic:
One guanidinium group & One carboxylate & Three hydroxyls & One –NH-C=O group!

Therefore this medicine is not active when given orally.

However, influenza virus enters host lung cells, so the compound can be administered with an inhalator.

Physical Chemical Requirements of (most) Oral Drugs

The Lipinski "Rules of Five"

"From the 50,427 compounds in the WDI (World Drug Index) File ....2245 were selected which are likely to have superior physico-chemical properties.

<u>Poor</u> absorption or permeation are more likely when:

- **The MWT is over 500**
- **There are more than 5 H-bond donors**
- **There are more than 10 H-bond acceptors**
- **The Log P is over 5**

... orally active therapeutic classes outside the 'rule of 5' are:
antibiotics, antifungals, vitamins and cardiac glycosides.

....We suggest that these few therapeutic classes contain orally active drugs that violate the 'rule of 5' because members of these classes have structural features that allow the drugs to act as substrates for naturally occurring transporters."

Lipinski et al., Advanced Drug Delivery Reviews 46: 3–26 (2001)

Medicines have to fulfil many requirements

Drugs are VERY Precious compounds

For *orally available* medicines a fine balance is required between :

(i) Sufficient capacity to cross membranes,
so it can be taken up from the digestive tract;
(ii) Sufficient water solubility,
so it can reach the site of action in sufficient concentrations.

Some other requirements of an ideal medicine are:
(iii) Not being converted to an inactive substance by human enzymes;
(iv) Not being cleared rapidly from the blood;
(v) No teratogenicity;
(vi) No mutagenicity;
(vii) No toxicity;
(viii) And more…

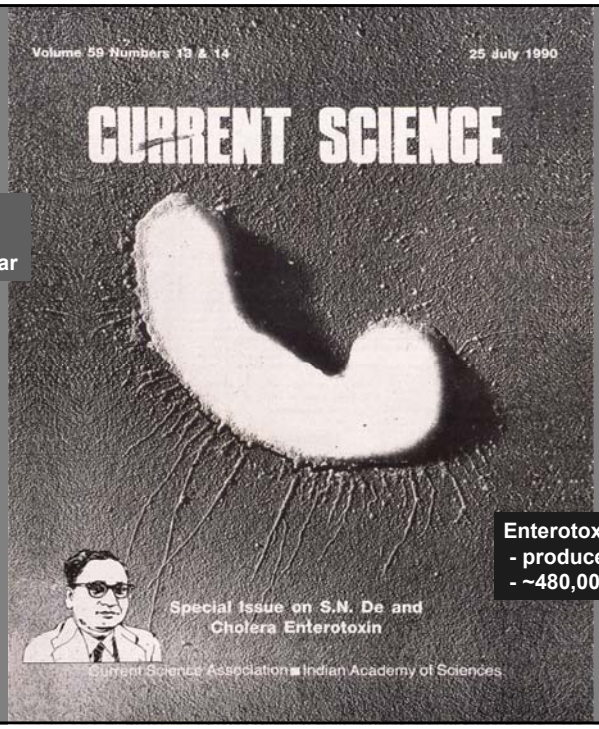
Hence, it is not really a surprise that it is a major challenge to make a new safe, effective, orally available, affordable medicine.

Multivalent Inhibitors of Cholera Toxin (CT)

produced by *Vibrio cholerae.*

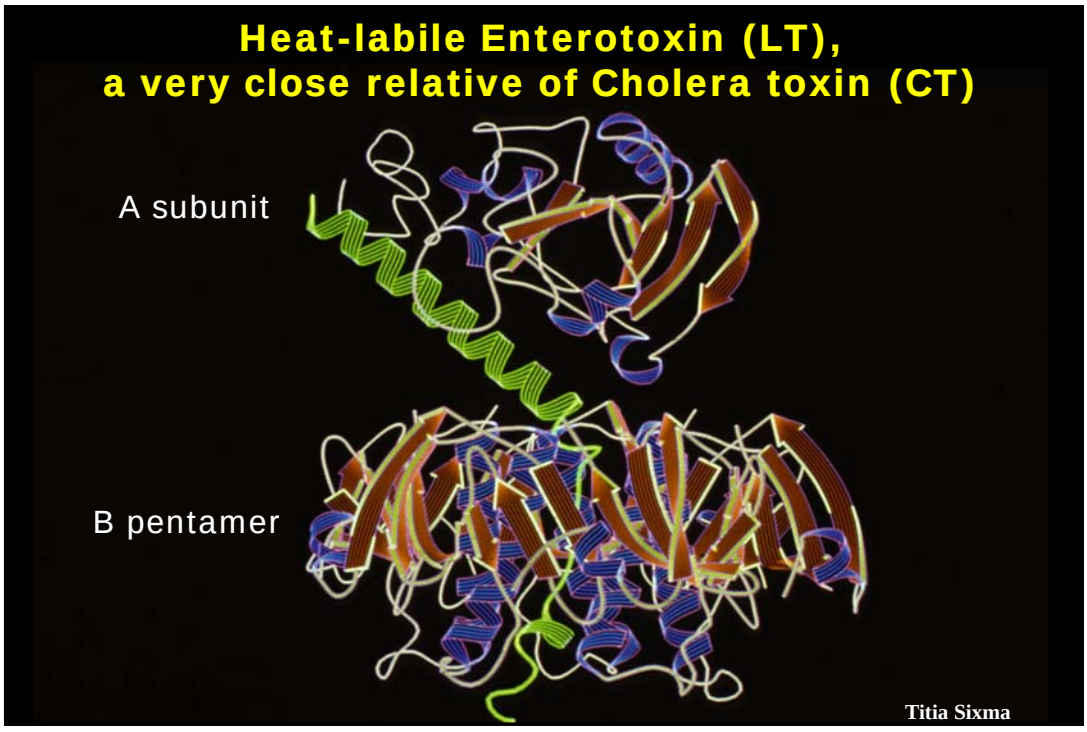
CT is a close relative of
Heat-Labile Enterotoxin (LT)
produced by enterotoxigenic *E. coli*,
the cause of much of children's and travelller's diarrhea

Vibrio cholerae :
- produces CT
- ~4000 victims per year

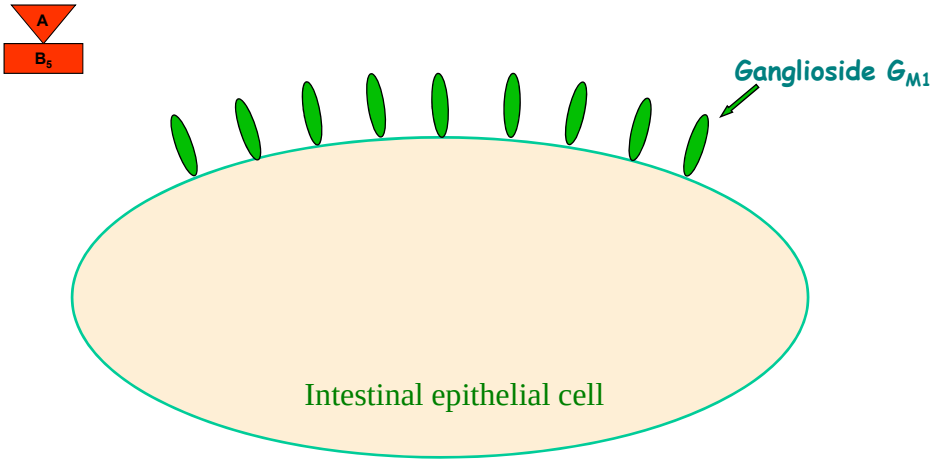


Enterotoxigenic *E. coli* :
- produces LT and ST
- ~480,000 victims per year

Heat-labile Enterotoxin (LT), a very close relative of Cholera toxin (CT)



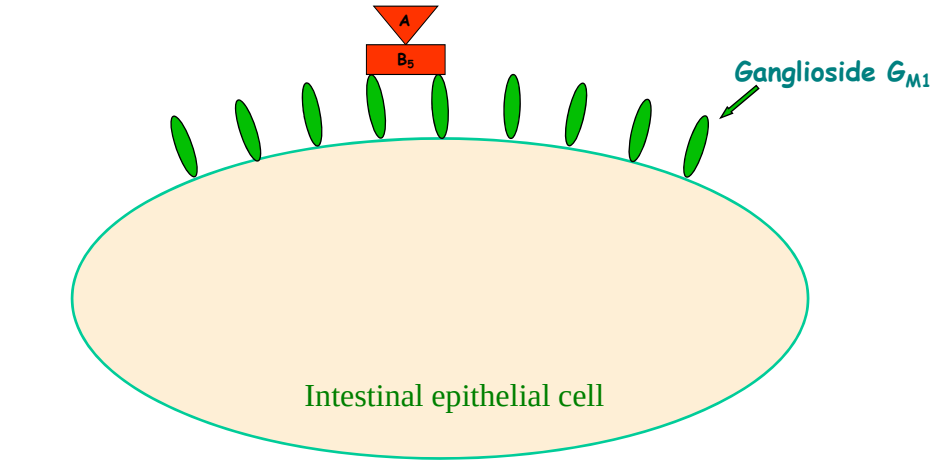
CT and LT Receptor Binding



CT : Cholera

LT : Traveller's & Children's diarrhea

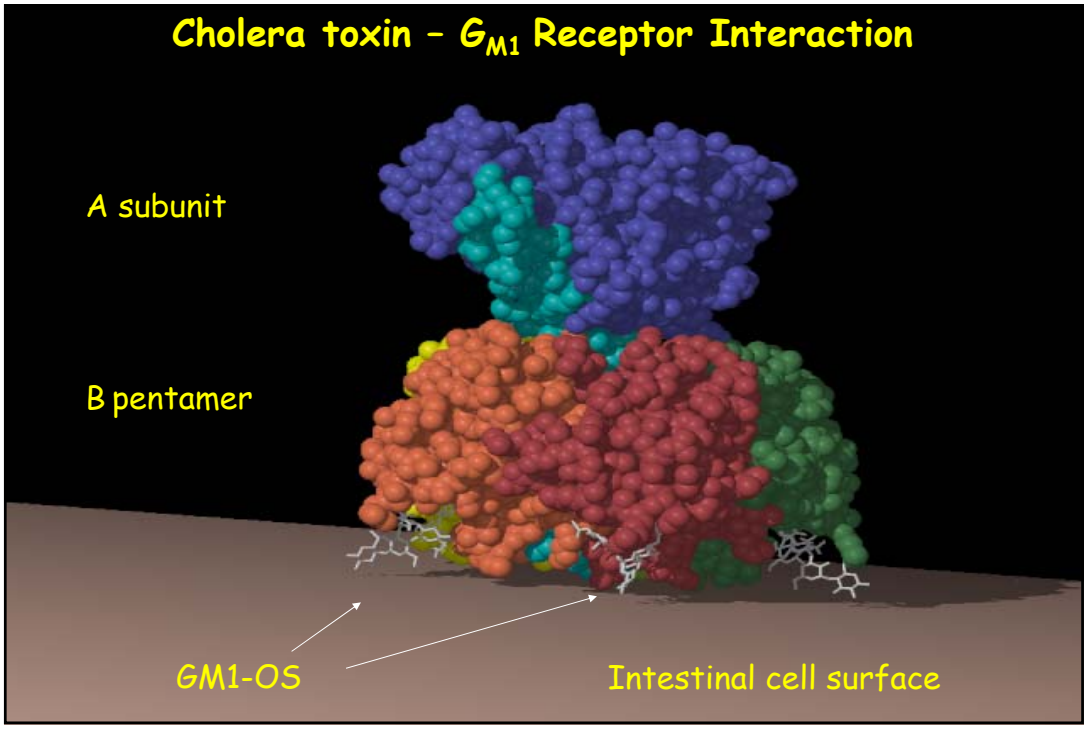
CT and LT Receptor Binding



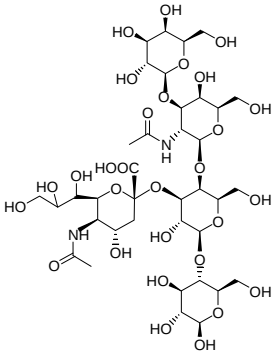
CT : Cholera

LT : Traveller's & Children's diarrhea

Cholera toxin – G_{M1} Receptor Interaction

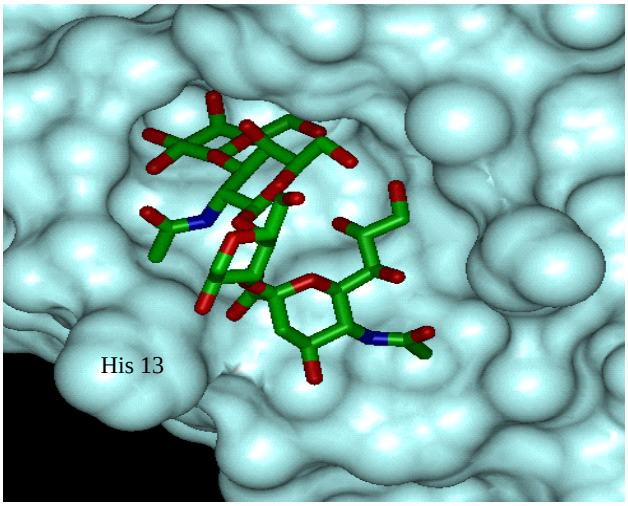


G_{M1} Pentasaccharide bound by CT



$IC_{50} = 14 \times 10^{-9}$ M

Extensive hydrophobic and H-bonding interactions

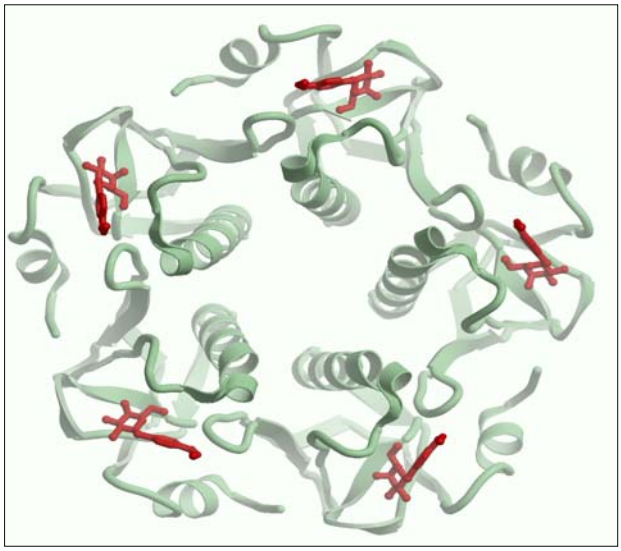


The enemy

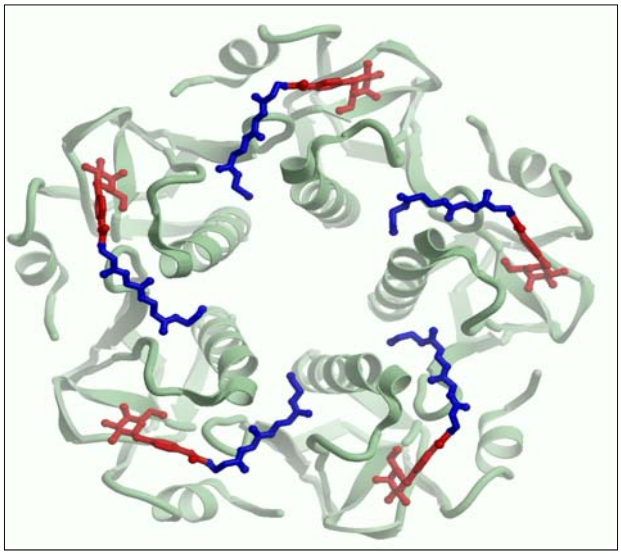
Joseph Martial

Steve Sarfaty
Ethan Merritt

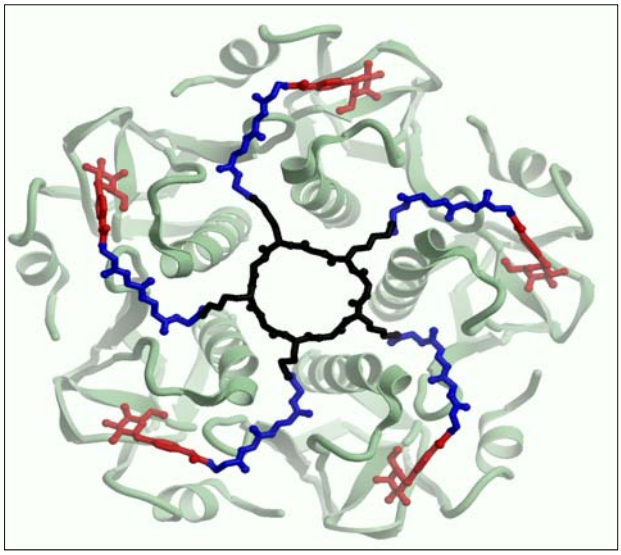
Five receptor binding sites



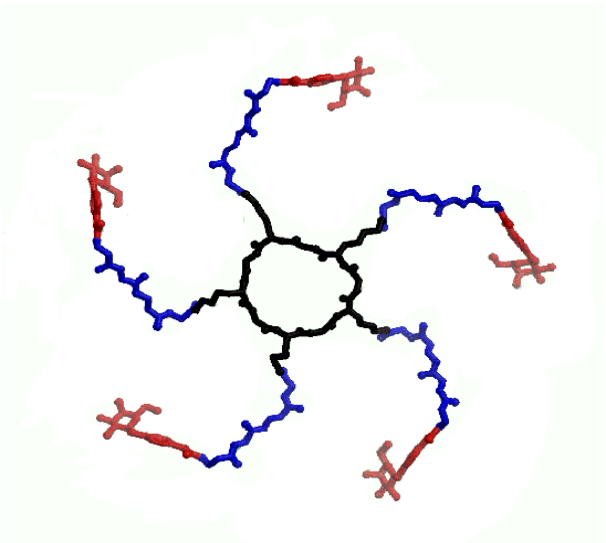
Making ligands longer



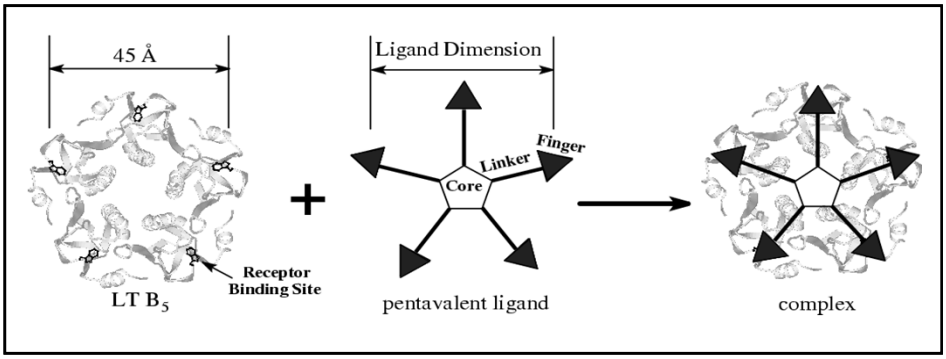
Ligand-Protein Complex



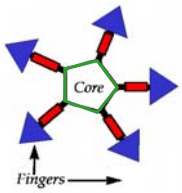
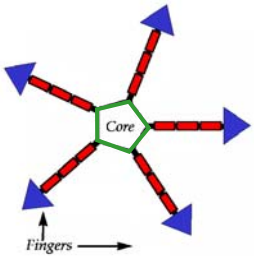
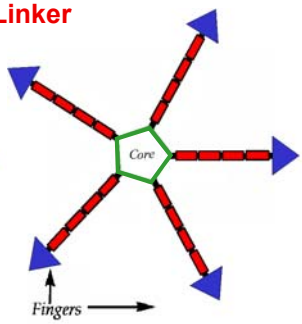
Pentavalent Ligand



THE PENTAVALENT CONCEPT

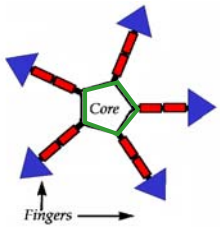
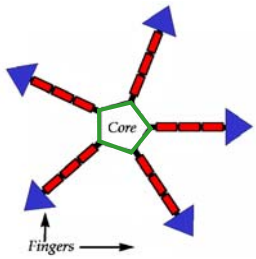
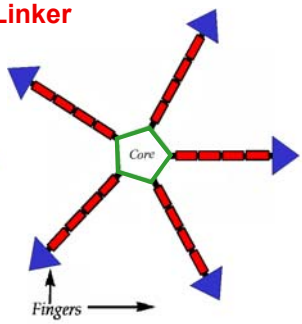


Gains in surface-receptor binding inhibition

One-Unit Linker	Two-Unit Linker	Three -Unit Linker	Four-Unit Linker
			
??? x Single Finger	???? x Single Finger	????? x Single Finger	?????? x Single Finger

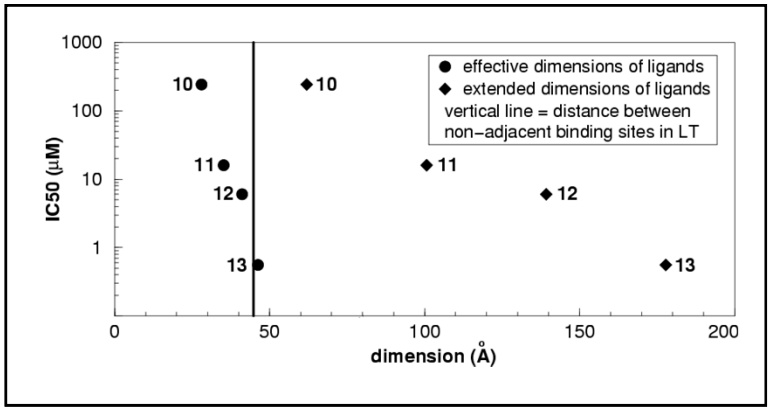
Erkang Fan and co-workers

Gains in surface-receptor binding inhibition

One-Unit Linker	Two-Unit Linker	Three -Unit Linker	Four-Unit Linker
			
240 x Single Finger	3,600 x Single Finger	10,000 x Single Finger	104,000 x Single Finger

Erkang Fan and co-workers

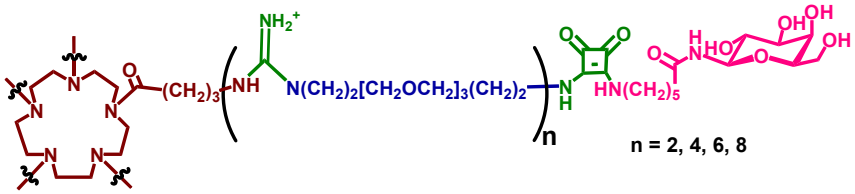
IC_{50} *versus* EXTENDED(◆) & EFFECTIVE (●) DIMENSIONS OF PENTAVALENT LIGANDS



What if even longer linkers?

Erkang Fan and co-workers

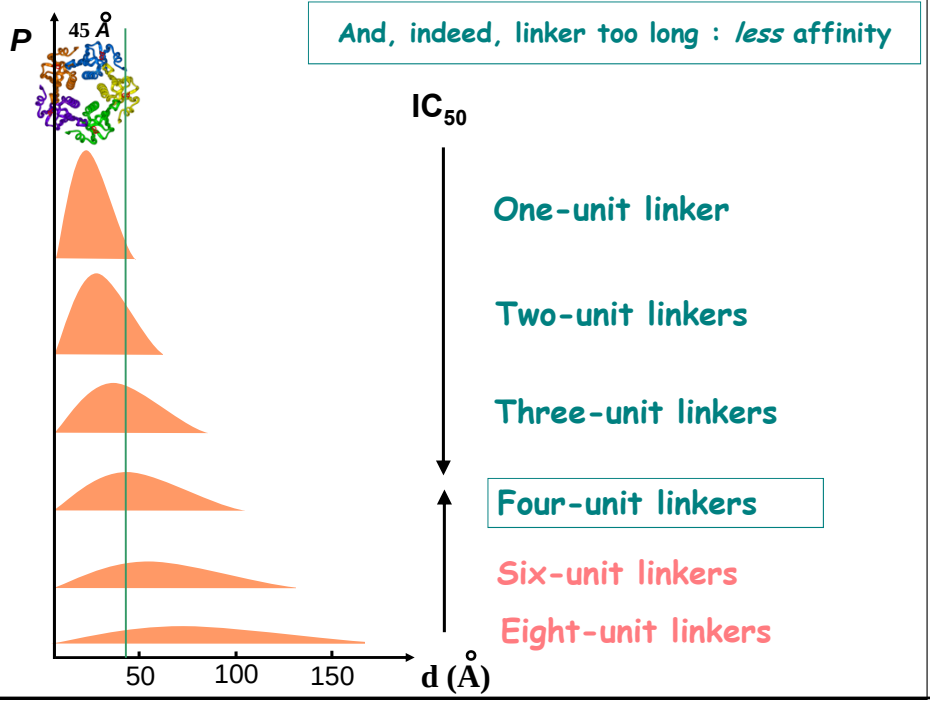
And, indeed, linker too long : *less* affinity



Linker Units	IC_{50} (μM)
n = 2	13.26 ± 0.95
n = 4	1.50 ± 0.10
n = 6	4.63 ± 0.46
n = 8	7.25 ± 0.38

(A single galactose "finger": IC_{50} = ~ 100 mM =~100,000 μM)

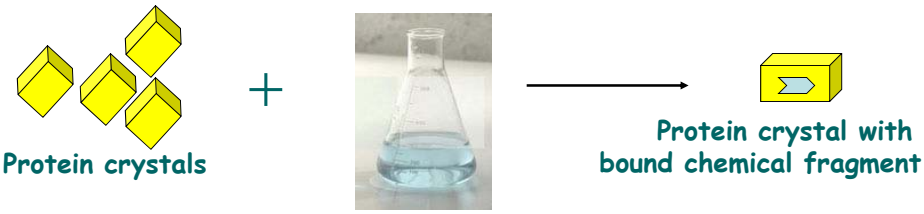
Erkang Fan and co-workers



Fragment Cocktail Crystallography

Fragment Cocktail Crystallography

Principle

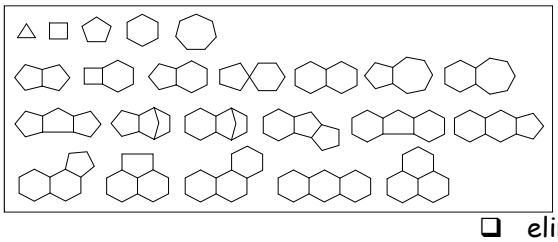


Probe protein pockets by soaking crystals
in well-designed mixtures of 5-10 different chemicals,
followed by crystal structure determinations,
Followed by "growing" or "linking" the fragments to obtain higher affinity.

Fragment Cocktail Crystallography

9,500 compounds
↓ *fragmentation*
626 fragments
↓ *isolate ring systems*
23 frameworks (at connectivity level)

ACD Compound Filtering
ACD= Available Chemical Database

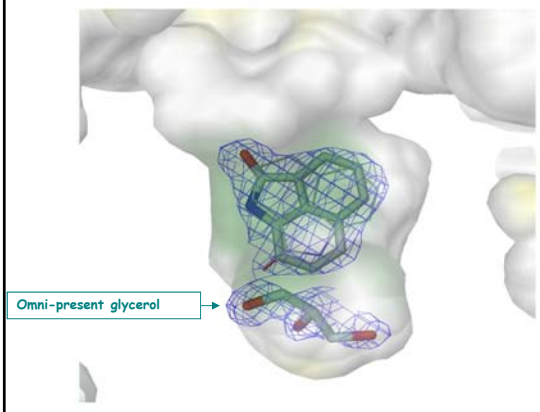


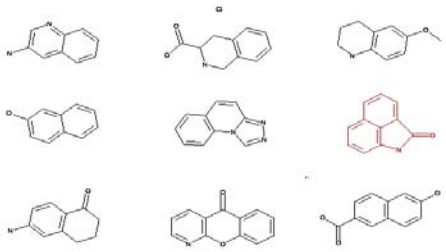
manual selection of compounds → 680 compounds *from each framework class*

- ❑ eliminate mutagens, known poisons
- ❑ no highly functionalized compounds
- ❑ retain Br containing compounds

Christophe Verlinde, Erkang Fan
http://faculty.washington.edu/verlinde/

Nucleoside 2-deoxyribosyltransferase (Tbru015777AAA) plus Cocktail #4

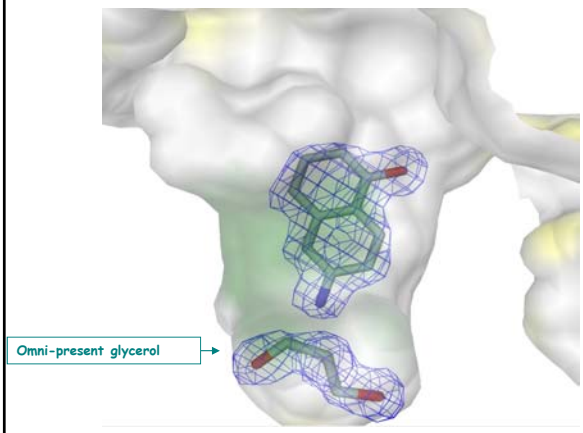


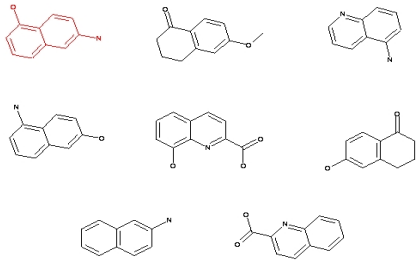


1,2-DIHYDROBENZO[CD]INDOL-2-ONE

Jürgen Bosch & Christophe Verlinde & Erkang Fan& & SGPP

Nucleoside 2-deoxyribosyltransferase (Tbru015777AAA) plus Cocktail #5





6-AMINO-1-NAPHTHOL

Jürgen Bosch & Christophe Verlinde & Erkang Fan & SGPP

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Computational Approaches

An excellent website with recent tools for Structure based drug design:

http://www.imb-jena.de/~rake/Bioinformatics_WEB/dd_tools.html

Major Journals with plenty SBDD:

J. Medicinal Chemistry

Chemistry and Biology

Nature Reviews Drug Discovery

J. Computer-Aided Molecular Design