Principles of Chemotherapy

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Cancer is a complex disease caused by genetic and epigenetic mutations.

- Simply, it is only unregulated cell division.
- "Traditional" chemotherapy highjacks mechanisms of mitosis.
- Understanding chemotherapy needs understanding of Biology 101.

* Of course it gets complicated.
Chemotherapy

- Merriam-Webster: Chemotherapy: *noun*: che • mo • ther • a • py
  - Medical: The use of chemical agents in the treatment or control of disease (such as cancer) or mental illness
- Word originated around 1910 by Paul Ehrlich
  - Developed the first treatment for syphilis, antiserum for diphtheria (Nobel prize in 1908)
  - He also developed the concept of “magic bullet”
- In the world of pharmacology chemotherapy can be used to treat:
  - Infectious disease
  - Cancer
History of Chemotherapy Begins...
Nitrogen Mustards were taboo and not used in battle, however
  - Ready to be used (feared Hitler would use when he was pushed)
Bomb raid on Bari, Italy on December 2nd, 1943
  - Sailors exposed had depletion of bone marrow stores and lymph nodes
Goodman and Gilman at Yale discovered murine models with lymphomas responded to nitrogen mustard therapy
  - Convinced a surgeon to treat a single NHL patient with a nitrogen mustard
  - Original trial done in 1943, but data kept secret until 1946
The Lesson of the 1940s

- Nitrogen Mustards: Alkylation of guanine nucleotides in DNA causing inhibition of cell division and ultimately apoptosis
- Showed promise however, responses to therapy was short and ultimately relapsed
- 1949: Sidney Farber (Dana-Farber), born in Buffalo, NY discovered folic acid accelerated childhood leukemia growth
  - Antifolates (aminopterin) induced significant remissions in pediatric leukemias
    - Short lived, and relapsed
- What contributed to failure?
Luria and Delbruck

- Go back to bacteria and how mutations arise...
- Took two groups of plates of bacteria and exposed them to a virus for infection
  - If resistance to the virus were due to exposure, then there would be the same number of resistant colonies
- Turns out the number of resistant colonies varied significantly between plates
- Resistance is due random mutations
- Cancer cells are no different from this:
  - Some are inherently resistant to a chemotherapy agent due to randomness alone
Luria and Delbruck

- Column A represents cultures where natural selection would look
  - Darwinism
- Column B is randomness
- Column B explains why chemotherapy is inherently resistant to single agent chemotherapy
Goldie – Coldman Hypothesis

- **Mathematical Model** predicts the likelihood of developing somatic mutations that lead to drug resistance
  - Probability of resistance to a drug is greater as the size of a tumor increases and/or the rate of division increases
  - Usually this develops even before the cancer is clinically detectable
- **Cancer is best treated by concomitant chemotherapeutic regimens** (multiple drugs given at the same time)
- **Principles taken so far:**
  - Tumors need to show sensitivity to each agent as a single agent
  - Drugs used in combination should have different mechanisms of action
Cancer Growth and Dynamics

- Gompertzian growth
- Fraction of tumors progressing thru cell cycle influences susceptibility
  - AKA growth fraction
- $10^9$ Cells!!! Clinical Symptoms
- As time increases:
  - Cells develop resistance inherently
  - Competition over nutrients
  - Less cells going through division
- Other fast growing cells:
  - GI/buccal mucosa
  - Hair follicles
  - Bone marrow
Types of Chemotherapy Regimens

- **Adjuvant chemotherapy**
  - chemotherapy given after surgery
  - Goal is to eradicate micrometastasis and decrease recurrence

- **Neoadjuvant chemotherapy**
  - chemotherapy given before surgery
  - Goal is to shrink the tumor for resection

- **Palliative chemotherapy**
  - Improve symptoms/ QOL
  - “Gentler” in nature

- **Curative chemotherapy**
  - More aggressive treatment
  - Traditionally associated with more toxicities
Cancer Growth and Regimens

[Diagram showing the progression of cancer growth and the effects of different treatments and interventions at various stages.]
Fractional Kill Hypothesis

- Also called “log-kill hypothesis”
- Assuming homogenous sensitivity to a drug, drugs will act on first order kinetics
  - They will eliminate a constant proportion of cells rather than a constant number
  - Cell kill is a logarithmic function
- Explains that multiple doses need to be given
- Partially explained by drugs only effecting specific steps in the cycle
  - Leukemic S-phase ~ 18 – 20 hours, cytarabine given Q12H
- Establishes the role of adjuvant therapy to treat micrometastatic disease or small volume disease
- Higher doses may give a larger proportion of cells killed
Norton – Simon Hypothesis

“Chemotherapy results in a rate of regression in tumor volume that is proportional to the rate of growth for an unperturbed tumor of that size,”

- Log – kill does not work in all situations, especially solid tumors
- Not all cells are rapidly dividing, high growth fraction

In other words, tumors are heterogeneous in nature
- Some are faster-growing, others are slower growing

Tumors are best eradicated by more frequent, lowest effective dose chemotherapy regimens
Dose Intensity vs Density

- The best scenario: highest dose of chemotherapy with the shortest interval possible
- Dose intensity (escalation): variable dose over a fixed unit of time
  - 90 mg/m$^2$ for 3 days vs 60 mg/m$^2$ for 3 days of etoposide
  - Subject to side effects
  - Analogous to concentration – dependent antibiotics
- Dose density: fixed dosed over a variable unit of time
  - AC (DD) regimen given every 14 days vs 21 days
  - Analogous to time – dependent antibiotics
Pharmacologic Properties of Drugs

- Why do so many promising drugs fail therapy once they go into humans?
  - Movement from petri dishes to humans is a big jump
- Pharmacokinetics: Study of drug pathway through the body
  - A: Absorption
  - D: Distribution
  - M: Metabolism
  - E: Elimination
- Pharmacodynamics: Study of the concentration of drug at the site of the effect
- Pharmacogenomics: Relationship with genomic variation on the individual on the kinetics and dynamics of the drug
Pharmacokinetics: The Basics

- Simple, IV bolus one-compartment model:
  - A: none. Bypassed when given IV
    - Otherwise drug levels would go up before they go down
  - D: none. Contained in one compartment (vasculature)
  - M: none
  - E: Constant

- Body Systems are far more complicated than this
Pharmacodynamics

- Assuming that concentration of blood has a relationship to that in tissue, establishes potency:

- How much is sufficient?

- At what cost does $E_{\text{max}}$ come?

- $EC_{50}$

- $LC_{50}$

- Kinetics/Genomics?
Drug Pathway Through The Body

- Highlights the overall complexity of the relationship of drug, effects and toxicities
- Mastering these with OPTIMIZE the effect of the drug while limiting toxicity
How is Dose Calculated?

- **Fixed Dose**: Dose is the same regardless of patient specific factors
  - Example: Pertuzumab (Perjeta) 840 mg IV x1, then 420 mg thereafter

- **Age Based Dosing**
  - Example: Dosing of chemotherapy in infants

- **Weight Based Dosing**: Dosing based on body weight in kg (TBW/IBW/ABW?)
  - Example: Bevacizumab 5 mg/kg IV every 2 weeks

- **Body Surface Area**: Most common
  - \[
  \sqrt{\frac{\text{weight (kg)} \times \text{height (in)}}{3600}}
  \]
  - Cisplatin 75 mg/m² IV every 3 weeks

- **Others**:
  - Calavert Equation for Carboplatin: Based on AUC and renal function
Eastern Cooperative Oncology Group (ECOG) Performance Status

- Assuming an equivalent BSA and same type/stage of cancer, is a 30 year old athlete going to tolerate the same therapy the same as a 70 year old chronic smoker on dialysis who cannot work?

- ECOG Performance Status (PS)
  - Standard to measure the impact of disease on daily living
  - Used extensively in clinical trials

- Changes of PS are one reason why doses and therapies change
  - Consider changes in PK/PD

- 70 year patient might start with lower dose or different therapy all together

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**Table 1. ECOG Performance Status categories**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Fully active, able to carry on all pre-disease performance without restriction</td>
</tr>
<tr>
<td>1</td>
<td>Restricted in physically strenuous activity, but ambulatory and able to carry out work of a light or sedentary nature, e.g., light house work, office work</td>
</tr>
<tr>
<td>2</td>
<td>Ambulatory and capable of all self care, but unable to carry out any work activities. Up and about more than 50% of waking hours</td>
</tr>
<tr>
<td>3</td>
<td>Capable of only limited self care, confined to bed or chair more than 50% of waking hours</td>
</tr>
<tr>
<td>4</td>
<td>Completely disabled. Cannot carry on any self care. Totally confined to bed or chair</td>
</tr>
<tr>
<td>5</td>
<td>Dead</td>
</tr>
</tbody>
</table>

Adapted from Oken, et al. 1982

ECOG = Eastern Cooperative Oncology Group
Review of Principles...

- The tales of the 1940’s taught that disruption of cell cycle can effect cancer growth
- Combination of agents may help prevent resistance and improve outcomes
- Cancer cell growth is not constant
- Chemotherapy can be given at different doses, frequencies and in combination with other modalities
- How the drug reacts in Petri dish is different from in the body
- Chemotherapy is toxic
- Chemotherapy is tailored to the patient and the cancer
How does Chemotherapy work?
Exploit the mechanisms
Cell Cycle and Chemotherapy

- **Cell cycle specific drugs:**
  - Drugs interfere with faster growing cells
  - S-phase (DNA synthesis) and M-phase (mitosis) are particularly important

- **Cell cycle non-specific drugs:**
  - Drugs that can interfere for more slow growing cells
  - Inflict damage whenever DNA is needed
    - Not just mitosis
  - Regimens contain both types of agents
Non-Cell Cycle Specific Chemotherapy

ALKYLATING AGENTS AND PLATINUM COMPOUNDS
Alkylating Agents

- Heterogenous group of loosely related compounds:
  - Nitrogen mustards (Mechlorethamine, cyclophosphamide, ifosfamide)
  - Ethyleneimines (thiotepa, altretamine)
  - Alkyl sulfonates (Busulfan)
  - Nitrosureas (Carmustine)
  - Triazenes (Dacarbazine)

- MOA: Form highly reactive carbonium ion intermediates which covalently link to amines, oxygens, or phosphates of DNA
  - N7 of guanine is highly susceptible
  - Other targets include N1 and N3 of adenine, N3 of cytosine and O6 of guanine

- Cell will then either try to repair the DNA and undergo cell cycle arrest
  - In cases where this does not work it will then undergo apoptosis
Alkylating Agents

- **Uses:** extensive
  - Solid Tumors: Breast cancers, prostate cancers, sarcomas, etc
  - Heme malignancies: leukemias, lymphomas, myeloma
  - Non-malignant conditions: rheumatic diseases

- Commonly used with cell cycle dependent agents

- **Resistance:**
  - Decreased permeation of active transported drugs
  - Increased concentrations of nucleophillic substances that bind and inactivate agents
  - Increased MMR and repair mechanisms
Alkylating Agents

Mechlorethamine

N7 of guanine
Cyclophosphamide (Cytoxan)

- One of the most extensive agents used in therapy
  - Given IV and PO
- Prodrug: a drug that is converted in the body to an active metabolite
  - Phosphoramide mustard
- Acrolein is toxic and causes hemorrhagic cystitis
- Used over a variety of diseases including
  - Rheumatic disease
  - Solid tumors
  - Heme malignancies

*Similar to ifosfamide*
Toxicities of Chemotherapy

- Bone Marrow Suppression (Mostly dose-limiting): affects dose density
  - Class effect but to varying degrees
  - Can lower platelets (thrombocytopenia), white blood cells (neutropenia) and red blood cells (anemia)
    - Can be used advantageously for bone marrow transplants
  - Acute myelosuppression: nadir of 7-10 days and recovery in 14-21 days
    - Cyclophosphamide, ifosfamide
  - Delayed myelosuppression: nadir in 4 – 6 weeks with gradual recovery
    - Carmustine
- Why the concern:
  - Thrombocytopenia: bleeding complications
  - Neutropenia: Opportunistic infections
  - Anemia: Fatigue, QOL, SOB
Toxicities of Chemotherapy

- **GI Toxicity:**
  - Mucosal ulceration
- **Chemotherapy Induced Nausea and Vomiting (CINV):**
  - Caused by various stimuli in the body and sent via redundant pathways
  - Varies depending on agent to varying degrees
  - Divided into 4 categories: High, Moderate, Mild, Minimal
    - Treatment is based on rating
  - Can start in hours (acute) and last for days (delayed)
  - Complications: GI bleeds, dehydration/malnutrition, kidney failure, esophageal tears
- **Constipation**
- **Diarrhea**
Platinum Complexes

- Behave similar to alkylating agents without alkylation
- MOA: Covalently bind on nucleophillic sites of DNA
  - The chloride, cyclohexane and oxalate molecules are displaced by water leaving a highly positively charged molecule
- Cis/carboplatin share similar activity and are somewhat interchangeable
- Resistance:
  - Cis/carboplatin share cross-resistance, while oxaliplatin does not
  - Loss of function of MMR proteins which would induce protein
  - Up-regulation of DNA repair genes
Cisplatin MOA
Platinum Complexes

- Spectrum of activity:
  - Cis/carboplatin: Solid tumor primarily
    - SCLC, NSCLC, Head and Neck, Bladder, Testicular
  - Oxaliplatin: GI tract cancers (Gastric, Pancreatic, CRC)

- Toxicities:
  - Cis/carboplatin:
    - N/V: Cisplatin more so
    - Renal toxicity: Cisplatin more so
    - Myelosuppression: carboplatin more so (thrombocytopenia)
  - Oxaliplatin:
    - Peripheral Neurotoxicity
    - Myelosuppression: thrombocytopenia
S-Phase: Antimetabolites

FOLIC ACID ANALOGS, PYRIMIDINE ANALOGS, PURINE ANALOGS
## Antifolates

<table>
<thead>
<tr>
<th></th>
<th>Pteridine ring</th>
<th>p-aminobenzoic acid</th>
<th>Glutamyl residues (1 to 6)</th>
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<td><strong>Folic Acid</strong></td>
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Antifolates (Methotrexate)

- 1948: Sidney Farber discovered aminopterin to treat childhood leukemia
- MOA: Dihydrofolate reductase (DHFR) inhibitor
  - Depletion of tetrahydrofolate, necessary for purine and thymidylate synthesis
- Resistance:
  - Decreased active transport into cell
  - Altered DHFR that impairs MTX binding or increased expression of DHFR
  - Increased efflux and active transport out of cells
- Side Effects:
  - Myelosuppression
  - Mucositis and intestinal inflammation
  - Nephrotoxicity
  - Neurotoxicity
Methotrexate MOA

- FH₂ is reduced by DHFR to FH₄ (needed for purine synthesis)
- MTX blocks DHFR which increases FH₂ polyglutamate (cytotoxic)
- Deoxyuridine monophosphate (dUMP) is converted to thymidine monophosphate (dTMP) (component of DNA)
- Leucovorin, an antidote can replete FH₄ stores and continue cycle
  - Used in poisonings and to high-dose MTX rescue
Methotrexate Uses

- Used in all types of cancers and include autoimmune conditions as well
  - Control graft-versus-host disease
- Doses can be given orally, intravenously or intrathecally
- High-Dose Methotrexate (> 1 g/m²/dose)
  - Requires therapeutic blood monitoring
  - Use of leucovorin “rescue”
  - Requires urine alkylinization
  - Penetrates CNS
    - Think large molecule, and blood-brain barrier
Pyrimidine & Purine Analogs

- Right is the pyrimidines
- Left is purines
- In theory:
  - Looks close enough to each that it can be substituted
  - They can be combined together and with antifolates in therapy
    - ALL regimens use various combinations
    - Considerable toxicities
5-Fluorouracil: Pyrimidine Analog

- MOA: Prodrug, is somewhat rate dependent (depends how it is administered)
  - Continuous infusion: inhibition of thymidylate synthase leading to thymidine deficiency
    - Leucovorin is administered prior to starting to stabilize 5FU-TS complex
  - Bolus: False base integration into RNA and DNA
- Pharmacogenomics: Clearance is mediated through dihydroypropyrimidine dehydrogenase (DPD)
  - Polymorphic
- Resistance:
  - Reduced conversion to active metabolite
  - Amplification of TS or alteration of TS binding site
  - Amplification of degradative enzymes
5-Fluorouracil MOA

```
[Diagram showing the metabolic pathway of 5-FU]

- **Continuous**:
  - DHFU
  - FdUMP
  - dUMP

- **Bolus**:
  - 5-FU
  - FUMP
  - FUTP
  - RNA dysfunction

- **Enzymes**:
  - OPRT
  - DPD
  - TP
  - TS

- **Pathways**:
  - FdUMP → FdUTP
  - DNA dysfunction
  - dTMP → dTTP
```
Colon cancer: FOLFOX regimen (developed at RPCI):
- Oxaliplatin 85 mg/m\(^2\) IV on day 1
- Leucovorin 400 mg/m\(^2\) IV given with oxaliplatin on day 1, followed by
- 5-FU 400 mg/m\(^2\) IV Bolus, then
- 5-FU 2.4 g/m\(^2\) IV given continuously over 46 hours

Side effects:
- Bolus: myelosuppression, angina
- Continuous: N/V, diarrhea, mucositis, hand-foot syndrome

Antidote: uridine triacetate
Cytarabine: Pyrimididine Analog

- Cytosine arabinoside (ara-C)
- MOA: Prodrug converted to ara-C-TP, false base integration into DNA leading to polymerase inhibition
- Side Effects: Dose dependent
  - Myelosuppression and rash
  - High dose (> 1 g/m² per dose)
    - Cerebellar syndrome
    - Conjunctivitis
6-Mercaptopurine: Purine Analog

- Developed in 1953 and used by Sidney Farber to treat pediatric ALL
  - Still used today
- MOA: inhibits purine synthesis and false integration into DNA or RNA
- Side Effects:
  - Hepatotoxicity
  - Myelosuppression
6-MP MOA

Resistance; down regulation

Polymorphic

Inactive

Non-enzymatic removal of nitroimidazole group

Inhibitor of de novo purine biosynthesis

Replicative DNA polymerase substrate
11% of caucasians have decreased TPMT activity
- TPMT*1: WT allele (fully active)
- TPMT*2, 3A, 3C: reduced function alleles

Loss of function alleles increase overall response but significantly increases myelosuppression

Testing is therefore warranted when severe myelosuppression with standard 6-MP doses
Natural Products

EPIPODOPHYLLOTOXINS, TAXANES, VINCA ALKALOIDS, CAMPTOTHECANS
Topoisomerase

**Type I Topoisomerase**

- Single Strand Break

**Type II Topoisomerase**

- Double Strand Break
Anthracycline: Doxorubicin

- Antracyclines: anti-tumor antibiotics, isolated from *S. peucetius*
  - Class includes: daunorubicin, epirubicin, idarubicin
- MOA: Multiple. Prodrug (doxorubicinol)
  - Major: Topoisomerase II inhibition - prevents re-ligation of DNA
  - Minor: DNA intercalation, and prevention of free radical formation
- Resistance: Upregulation of P-gp (MDR1) that efluses doxorubicin out
- Side Effects:
  - Cardiotoxicity (additive effects with concurrent cyclophosphamide)
    - Lifetime dosing limits
  - Myelosuppression
  - Alopecia
  - Mucositis/ N/V
  - Vesicant
  - Red discoloration of: urine, tears, CNS fluid
Etoposide

- Extract from roots of *Podophyllum peltatum* (mandrake plant)
- MOA: Topoisomerase II inhibitor via stabilization of TOP2 complex
  - Accumulation of cells in S phase (G$_2$ Phase as well)
  - Leads to apoptosis
- Side Effects:
  - Myelosuppression
  - Alopecia
- Resistance:
  - P-gp up-regulation
  - Repair of DNA breaks
  - Alterations to Topoisomerase II
Irinotecan

- Isolated from a Chinese tree *Camptotheca acuminata*
- MOA: Prodrug, Topoisomerase I inhibition
  - Active metabolite is SN-38
  - SN-38 is inactivated via UGT1A1
- Side effects:
  - DIARRHEA
  - Alopecia
  - Myelosuppression
- Resistance:
  - P-gp upregulation
- UGT1A1 is polymorphic, 10% of patients are homozygous for *28
- *28 is loss of function allele, increased severity of diarrhea
  - Can last for days
- Heterozygous patients also have more profound diarrhea
Antimitotic Agents

- Building blocks of microtubules consist of two subunits, an α and a β
- Microtubules grow from the spinal pole towards the metaphase plate
  - Repetitive assembly of both subunits
- Microtubules bind to kinetochore and then disassemble back to the spindle pole
- Drugs that target mitosis target microtubules
  - Assembly
  - Disassembly
Taxanes vs Vincas

Vinca alkaloids prevent microtubule assembly.

Alpha tubulin
Beta tubulin

Taxanes prevent microtubule disassembly.
Taxanes: Polymerizing agents

- Discovered from *Taxus brevifolia* (Pacific Yew Tree)
- MOA: Inhibit depolarization by binding to β-tubulin, causing mitotic arrest
  - Paclitaxel, docetaxel, cabazitaxel, ixabepilone, nab-paclitaxel
- Drugs are extremely hydrophobic, use castor oil for dissolution
  - Caster Oil causes anaphylactic reactions
- Side Effects:
  - Myelosuppression
  - Alopecia: full body
  - Neuropathy
  - Myalgias
  - Edema
- Resistance:
  - P-gp up-regulation (substrate)
  - Alteration of tubulin structure
Vinca Alkaloids: Depolymerization

- Isolates from *Catharanthus roseus* (Madagascar periwinkle)
- MOA: Inhibition of polymerization by binding to β–tubulin and stabilizing it
  - Vincristine, vinblastine, vinorelbine
- Fatal if given intrathecally (No vines in the spine!)
- Side Effects:
  - Vesicant
  - Neurotoxicity: Vincristine
    - Peripheral neuropathy
    - GI: constipation
  - Myelosuppression: Others
- Resistance:
  - P-gp upregulation
Activities...

- **Heme Malignancies:**
  - Leukemia: Anthracyclines (doxorubicin), cytarabine, fludarabine, vincristine, etoposide, cyclophosphamide
  - Lymphoma: Ifosfamide, cyclophosphamide, methotrexate, cisplatin, vincristine, doxorubicin

- **Solid Tumors:**
  - GI: 5-Fluorouracil, oxaliplatin, irinotecan
  - Breast: cyclophosphamide, methotrexate, doxorubicin, taxanes, platinun
  - Lung: Cisplatin, etoposide, taxanes, pemetrexed, gemcitabine
  - Prostate: taxanes
These are “traditional” chemotherapeutic agents
Agents can be used in a variety of cancers
Members of the same drug class can have a different side effect profile
Regimens are combinations of multiple mechanisms of action
  - Also balancing of side effects
Drugs administered in different ways can alter their effects in the body
Drugs respond differently in different patients
  - Change in toxicity profiles
Side effects can be dose dependent
Chemotherapy Regimens

- Agents *obviously* need to be active against a given tumor
- Select agents with different:
  - MOA
  - Resistance
  - Dose-limiting toxicity
- Combinations needed to maximize kill and limit resistance
  - Remember principles
Regimen known as CHOP is a cure for lymphomas even in stage IV

- C: Cyclophosphamide: alkylation of DNA (non-specific)
  - Myelosuppression, NV, Renal dysfunction, alopecia

- H: Doxorubicin: Topoisomerase II inhibitor (S-phase)
  - Cardiotoxicity, NV, myelosuppression, mucositis

- O: Vincristine: Antimitotic agent (M-Phase)
  - Neuropathy

- P: Prednisone: Not covered but immunosuppression
  - Increased appetite, hyperglycemia, hypertension

Note the mechanisms of actions of the agents
  - Note the toxicities as well
As time goes by...

- Traditional agents = indiscriminate killer of cells
  - How do we know good cells from bad cells?
  - Assumes that ALL rapidly dividing cells are bad
  - Assumes that ALL slow dividing cells are good
- Drug development has had some serendipitous discoveries:
  - 1980s: All-transretinoic acid (ATRA) in APL
    - Targets immature leukemic cells and causes differentiation to force differentiation
  - 1980s: Tamoxifen in hormone positive breast cancer
    - Targets cells that over-express ER/PR
- Therapy is moving towards more targeted approaches
  - Moving from carpet-bombing to tactical bombing
Targeted Therapy

- More appropriately termed, molecularly targeted therapies
  - Target specific genes, proteins or tissue environments
- Specific to subtypes of cancer
  - Requires an understanding of cancer pathophysiology
  - Requires genotyping and effecting signal pathways
- What makes a good target?
  - Targets only present on/in cancer cells
  - Targets more commonly found on/in cancer cells
  - Or target both cancer and normal, but normal cells that regenerate
Small Molecule Inhibition

- AKA Tyrosine kinase inhibitors (TKI)
  - Intracellular monoclonal antibodies
- Tyrosine kinase: phosphorylate from ATP tyrosine, serine and threonine, signaling pathway for survival and proliferation
  - Deregulation by various means is one way cancer cells survive
- Class of drugs mainly acts through competitive inhibitors of the ATP-binding domain
- May also target other downstream enzymes active in signal transduction
  - RAS
  - RAF
4 Key Issues (Pearls)

- 4 issues with these drugs to consider:
  - Interactions with CYP 3A4: Drug interactions
    - Interaction with P-gp (MDR1)
  - Administration with or without food
    - Food interactions can cause either an increase or decrease in exposure
  - Acidity of the stomach
    - Drugs that effect acidity (PPIs and H2 Blockers)
  - Compliance
    - Patients need to take their medication
Chronic Myelogenous Leukemia

DEATH SENTENCE TO SUCCESS STORY
Philadelphia chromosome t(9:22)

- Translocation of the long arms of chromosomes 9 & 22 called Philadelphia Chromosome (Ph+)
  - Abelson murine leukemia gene (ABL)
  - Breakpoint cluster region (BCR)
- Forms fusion oncogene BCR-ABL
- ABL contains TK p210 that regulates proliferation
- BCR-ABL is a TK that is cytokine independent on-signal
- This is there 95% of time
CML Phases

- Chronic Phase (3-5 years)
  - Asymptomatic

- Accelerated Phase (months)
  - Blasts 10 – 19%
  - Platelets < 100,000 or > 1,000,000
  - Clonal evolution: extra abnormalities accumulate
  - Non-specific symptoms: fatigue, night sweats, fever

- Blast Crisis (~1 year)
  - Blasts > 20% (ALL or AML type leukemia)
  - Extramedullary blast proliferation
Imatinib (Gleevec)

- 1st agent in class, revolutionized CML treatment
- MOA: Inhibition of BCR-ABL tyrosine kinase active conformation (Philadelphia Chromosome + CML)
  - Also targets: SRC, c-KIT kinases, PDGFR (Multikinase)
- Side effects:
  - Edema, rash, nausea, myalgias
  - Myelosuppression, hepatotoxicity
- Resistance:
  - BCR-ABL kinase binding domain mutations
  - Overamplification
Imatinib

Alteration of binding site
# TKI Class side effects

<table>
<thead>
<tr>
<th>Toxicity</th>
<th>Management Strategy</th>
</tr>
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<tbody>
<tr>
<td>Neutropenia</td>
<td>Hold until recovery, potential dose reduction</td>
</tr>
<tr>
<td></td>
<td>Myeloid growth factors may be considered</td>
</tr>
<tr>
<td>Anemia</td>
<td>ESAs not supported in patients with myeloid malignancies.</td>
</tr>
<tr>
<td>Thrombocytopenia</td>
<td>Hold until recovery, potential dose reduction</td>
</tr>
<tr>
<td>Rash</td>
<td>Topical or systemic steroids</td>
</tr>
<tr>
<td></td>
<td>Dose reduction, interruption or discontinuation</td>
</tr>
</tbody>
</table>
Dasatinib (Sprycel)

- 2nd generation BCR-ABL inhibitor; 325 times more potent than imatinib
- MOA: Bind to active and inactive conformations of ABL kinase domain
  - Active in nearly all BCR-ABL mutations resistant to imatinib (except T315I)
- Dose: Chronic Phase: 100 mg po daily
- Pearls:
  - Can be used first line or after progression
  - Cannot use proton pump inhibitors or H2 blockers (gastric reflux agents)
- Toxicities unique to dasatinib:
  - Pulmonary arterial hypertension: D/C therapy
  - Edema (pleural effusion, pericardial, ascites)
Nilotinib (Tasigna)

- 2ND Generation BCR-ABL TKI, 30 times more potent inhibitor than imatinib
- MOA: Binds to closed conformation and exhibits a higher affinity and better fit than imatinib
  - Also inhibits c-KIT and PDGFR
- Dose: Chronic 300 mg PO twice daily
- Pearls:
  - Can be used first line or after progression
  - Monitor EKG with QTc, monitor electrolytes
- Toxicities unique to nilotinib:
  - QTc prolongation (cardiac arrhythmias)
  - Elevation of serum lipase
  - Hepatic toxicity
  - Peripheral arterial occlusive disease
Initial selection of TKI therapy

- Potency differences do not change overall survival
- Choose ONE: imatinib, dasatinib, nilotinib, considering:
  - Toxicities
  - Age or ability to tolerate therapy
  - Comorbid conditions
  - Risks
- 2nd generation have faster time to response but long-term survival is not established yet
- Progression or lack of effect, move to one of the other agents (except imatinib) or:
  - Bosutinib
Bosutinib

- 2nd Generation TKI, 200 times more potent than imatinib and has activity in imatinib, dasatinib and nilotinib resistance
- MOA: Inhibition of BCR-ABL and SRC, Lyn and Hck kinases
- Dose: 500 mg PO daily
- Pearls:
  - Failed to beat imatinib in head to head first line, therefore reserved for treatment failure
  - PPI decrease concentrations
- Toxicities unique to bosutinib:
  - Hepatic toxicity
  - Diarrhea
Third line therapy and beyond

- A second or third TKI may be considered
  - Again, if imatinib is not used first line, it can't be used after failure of other agents
- Allogeneic stem cell transplant
- Omacetaxine (Synribo): indicated in failure or intolerance of TWO or MORE TKIs:
  - *Cephalotaxus harringtonia* alkaloid that binds to reversible ribosomal proteins
  - Does not bind to BCR-ABL
  - Give twice daily Sub-Q, limits compliance:
    - 1.25 mg/m2 SQ twice daily x 14 days/ 28 days
T315I CML

- Clinical Trial?
- Omacetaxine can be used (MMR 19% patients, clone reduced to LLQ 61%)
- Ponatinib (Iclusig): Indicated ONLY in T315I mutations or in those where no other TKI is indicated
  - Black Box Warning: Increased frequency of life-threatening clots and narrowing of blood vessels
  - Only available through ARIAD PASS special access program for vascular occlusion, CHF and hepatotoxicity
- MOA: Inhibits BCR-ABL as well as VEGFR, FGRF, PDGRF, EPH, SRC, KIT, RET, TIE2, FLT3
  - Explains side effects
- Dose: 45 mg PO daily
  - Avoid PPIs with these
Primary resistance (hematological criteria) in newly diagnosed CP-CML is rare:
- 25% of patients do not obtain CCyR with imatinib

Secondary Resistance more common:
- Conformational changes in the binding site in BCR-ABL caused by point mutations
- T315I is the mutations with the highest risk of resistance (gatekeeper mutation)
- ID’ind the mutations may be helpful in selecting alternatives

Consider mutational analysis for:
- CP-CML with inadequate initial response
- CP-CML with any loss of response
- Progression
Compliance: pharmacy’s role?

- Patient education on adherence/ monitoring of adherence is crucial
- ADAGIO trial: what does non-adherence do with imatinib?
  - Adherence < 85% had a higher probability of losing CCyR at 2 years (27% v. 1.5%)
  - Only independent predictor for achieving a complete molecular response
- Preliminary data extrapolates to dasatinib and nilotinib
ACCELERATED PHASE

- Goal is to return to chronic phase
- Perform mutational analysis prior to switching therapy
- Accelerated Phase (AP-CML): All TKIs have shown to induce favorable responses
  - Imatinib 600 mg daily
  - Dasatinib 140 mg daily
  - Nilotinib 400 mg twice daily
  - Bosutinib 500 mg daily
- Note doses for 1st line are higher
- Can also use omacetaxine or alloHSCT
BLAST CRISIS

- High-dose induction chemotherapy used with response rates 25 – 60%
- Add a TKI to chemotherapy in BP-CML
  - Imatinib, dasatinib, nilotinib, bosutinib
- Recommendations:
  - Combination chemotherapy with TKI specific to AML or ALL
Message on Targeted Therapy

- Value in “me too,” drugs (drugs that multiple members are FDA-approved)
  - 5 CML TKI agents approved and they have defined roles in therapy
- Both similarities and differences between agents matter:
  - Does the difference provide an advantage in any way?
    - Toxicity profile (off-target effects)
    - Efficacy in treatment failure situations (place in therapy)
  - Does the similarity mean they are equivalent/interchangeable?
    - Can information be extrapolated from one agent to the next?
- Changing the dosing strategies for different scenarios:
  - Dosing is may increase effect but also increase toxicity
  - Is this worth it?
- Compliance is an important consideration
Shifting Gears...Final Remarks...
Pharmacologically active agents that don’t discern cancer cells from healthy cells

Studies show that these agents increase the risk of cancer in healthcare workers

Also effect outcomes of pregnancies:
  - Both men and women should heed caution while conceiving, pregnant or nursing

In clinical practice, agents are prepared and handled in Biological Safety Class II Cabinets
  - Users wear gowns, gloves and in some cases respirators

Please refer to OSH and NIOSH standards on safe handling practices

Protect yourself and learn the rules!

Gloves should be ASTM-tested against chemotherapy
One Last Toxicity...

- Large percentage of drug development is in oncology (~60%)
- Financial Toxicity is a big word these days..
  - Financial harm on patients caused by accepting costly therapies
- Consider the survival benefit/ cost relationship
  - Many agents cost several thousand for each cycle to add only a few months of overall survival benefit (at best)
- Consider imatinib cost $5,000 a month over 10 years ago
  - Now it costs $10,000 for the same drug and dosage form
  - Immunotherapies costing > $100,000 a year
  - Anti-nausea medications cost ~ $1,000 a cycle
- These costs are unsustainable for patients, hospitals and insurance companies
## Table 1. Proposed Financial Toxicity Grading Criteria

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lifestyle modification (deferral of large purchases or reduced spending on vacation and leisure activities) because of medical expenditure&lt;br&gt;Use of charity grants/fundraising/copayment program mechanisms to meet costs of care</td>
</tr>
<tr>
<td>2</td>
<td>Temporary loss of employment resulting from medical treatment&lt;br&gt;Need to sell stocks/investments for medical expenditure&lt;br&gt;Use of savings accounts, disability income, or retirement funds for medical expenditure</td>
</tr>
<tr>
<td>3</td>
<td>Need to mortgage/refinance home to pay medical bills&lt;br&gt;Permanent loss of job as a result of medical treatment&lt;br&gt;Current debts &gt; household income&lt;br&gt;Inability to pay for necessities such as food or utilities</td>
</tr>
<tr>
<td>4</td>
<td>Need to sell home to pay for medical bills&lt;br&gt;Declaration of bankruptcy because of medical treatment&lt;br&gt;Need to stop treatment because of financial burden&lt;br&gt;Consideration of suicide because of financial burden of care</td>
</tr>
</tbody>
</table>
Any Questions?
References


